COAL

and the

Prevention of Explosions and Fires in Mines

by

JOHN HARGER

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Coal, and the Prevention of Explosions and Fires in Mines.

By JOHN HARGER,

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CONTENTS.

CHAPTER I.

THE NATURE OF COAL AND ITS OCCLUDED GASES.

Origin of Coal; Constituents of Coal; Gases in Coal; Gas occluded by Coal and Coal Dusts.

CHAPTER II.

COMBUSTION.

Combustion; Ignition Temperature; Calorific Power; Calorific Intensity; Limits of Ignitability of Gas Mixtures; Extinction of Flames in Enclosed Volumes of Air.

CHAPTER III.

COMBUSTION (*continued*).

Rusting; Slow Oxidation or Autoxidation; Influence of Catalysts on Combustion; Surface or Flameless Combustion.

CHAPTER IV.

RESPIRATION.

Composition of Air; General Functions of Oxygen and Carbon Dioxide; The Effects of Reduced Percentage or Tension of Oxygen; The Influence of Carbon Dioxide.

CHAPTER V.

RESPIRATION (*continued*).

The Influence of Water Vapour and Temperature; Influence of Carbon Monoxide; Influence of Sulphuretted Hydrogen; Influence of Nitrous Fumes.

CHAPTER VI.

THE MECHANISM OF EXPLOSIONS.

CHAPTER VII.

THE RÔLE OF COAL DUST IN EXPLOSIONS.

PART I. HISTORICAL.

History of our Knowledge regarding the Influence of Dust; Evidence of Witnesses from the 1894 Report of the Royal Commission; Extracts from Reports on Colliery Explosions; 1909 Report of the Royal Commission; Source and Distribution of Coal Dust.

CHAPTER VIII.

COAL DUST EXPLOSIONS (*continued*).

The Phenomena of Dust Explosions; Experimental Explosions; Influence of the Quantity and Quality of Dust; Influence of Shot Firing; Influence of Ventilation; Influence of Fire-damp.

CHAPTER IX.

COAL DUST EXPLOSIONS (*continued*).

The Influence of the Percentage of Oxygen; Influence of Carbon Dioxide; The Iowa Mine Explosion.

CHAPTER X.

PREVENTION OF EXPLOSIONS.

Four Methods: Removal of Dust; Reduction of Oxygen Percentage; Watering; Stone-dusting.

CHAPTER XI.

GOB FIRES: THEIR PHENOMENA.

Spontaneous Combustion; Early work on the Spontaneous Combustion of Coal; Phenomena of Gob Fires; Varieties of Gob Fires; Influence of Weather; Influence of Timber; Supposed Influence of Pyrites; Work of Haldane and Meachem; Theory of the Origin of Gob Fires.

CHAPTER XII.

GOB FIRES (*continued*); THEIR TREATMENT.

Dangers and Expense of these Fires; Treatment of Cavities; Self-extinction of Heatings; Early Detection of Gob Fires; Use of Inert Gas in dealing with them; Hydraulic stowage; Conclusion.

APPENDIX.

Statistics: Notes on the Fire-proofing of Timber. Hygrometrical Table.

PREFACE.

This little book is an attempt to embody, in simple and convenient form, the main facts regarding our knowledge of coal and the chemistry of respiration, combustion and explosion, in the light of the most recent research. The information it contains has been collected from Government blue books and from many papers in various journals; some of it is the result of the author's original work at coal pits and in the chemical laboratories of Liverpool University.

It is hoped that this concise account will help to provide practical mining people with the fundamental knowledge that is essential for a proper understanding of the physical and chemical changes (including explosions and fires in mines) that occur during the extraction of coal. Possibly it is because no suitable presentation of our modern knowledge of these matters has yet been given that so many mining officials, even among those with scientific training, are ignorant of facts that are vitally important. For example, the author has met many mining people who believe that air in which a lamp will not burn is unfit to breathe, and who are unaware that a candle will not burn in air that contains 17 per cent. of oxygen and burns only feebly in air with 18 per cent. of oxygen.

Many erroneous statements, the falsity of which was long ago shown, still appear in some text books and obtain wide credence. Indeed there are many mining officials who have held and preached these false opinions for so long that they can hardly be convinced of their error. And even those mining men whose knowledge of the fundamental facts of respiration and combustion is recent and accurate usually fail to recognise the significance of these facts and the application of them to the prevention of explosions and fires.

But the day is fast approaching when such official ignorance of vital matters affecting the safety of mines will no longer be tolerated by the men who work the pits and by the general public. At the present time, work in many collieries is needlessly dangerous. If the exigencies of time and management do not allow the officials to acquire the necessary knowledge, it should be frankly recognised that the equipment is incomplete without a chemist to advise on these points and to obtain the requisite information (by analyses on the spot) regarding the air supply, the composition of the mine atmosphere in different parts and the properties of the local coal-dusts. From the knowledge so obtained, simple modifications in the method of working could be made which would remove risk and anxiety and effect a big saving in expense.

Hitherto, research work on coal-mine explosions has been conducted mainly by amateurs and by Government Commissions, the work being allocated by a Committee. But this is evidently not the proper course. The results obtained so far, working in this way, have been little more than a corroboration of facts already well known to mining people. What is wanted is a method of *preventing* explosions, not of *making* them.

The chemical problems connected with explosions and spontaneous fires are intricate and offer a vast field for research. Progress would be more rapid if there was cooperation between mine managers and the research staffs at Universities. But our present knowledge, though far from complete, is sufficient to enable mines to be worked in safety. It is known beyond doubt that, whatever may be the initial cause of a coal-mine explosion, all big explosions are spread by coal-dust. Therefore the immediate course for a mining engineer is to remove the dust or render it harmless.

A considerable portion of this book is given to a discussion of methods for effecting this, and it is shown how every mine can be rendered safe from explosions and from fires.

The author is much indebted to his friend Mr. W. M. Hooton, M.A., M.Sc., F.I.C., for help in arrangement and proof correction; to Professors Baly and Donnan for their kindness in providing facilities for research at Liverpool University; to Professors Leonard Hill and Benjamin Moore and Dr. J. S. Haldane for private communications regarding the mechanism of respiration; to Professor V. B. Lewes for information on fireproofing timber; and to Mr. W. H. Chambers for the means of obtaining practical knowledge of gob-fires at the mines.

Coal and the Prevention of Explosions and Fires in Mines.

CHAPTER I.

THE NATURE OF COAL AND ITS OCCLUDED GASES.

Coal represents the accumulation of solar energy, fixed by luxurious forest growths in carboniferous and other geological ages, over almost incredible periods of time.

By combining this supply of coal with oxygen, man has been able to utilise much of its energy, and the transformation of this into heat and power has, in a single century, done more to change the mode of life and habits of thought of mankind than has been effected by all political, social, and personal influences combined. Unless new methods of obtaining power are discovered, the future progress of civilisation depends on its supply of coal and other fuels.

Recent research on radioactive substances has shown that enormous quantities of energy exist in the atoms of elements, and that in some few cases the energy is being slowly evolved. But so far no method has been devised of either hastening or retarding this evolution of energy and transformation of one element into another. The possibilities are enormous, but the difficulty of tapping these supplies may be equally so.

By transmutation into other kinds of matter an ounce of radium liberates as much energy as is produced by the combustion of about seven tons of coal, but it takes 2,000 years to do this by the present process of natural decay.

It is very possible that the primary source of natural energy, which has maintained the regular movements and stability of the universe over thousands of millions of years, is this transmutation of the atoms of one elementary substance into others.

In particular the maintenance of the sun's temperature over millions of years, is probably due to energy liberated in this manner and not to that supplied by combustion, as was formerly supposed. In fact the temperature of the sun and of many fixed stars is far too high to be caused by anything in the nature of combustion. In some stars the temperature is estimated at 30,000° C.,* while the highest temperature obtainable in electric furnaces is about 4,000° C.

ORIGIN OF COAL.

The exact nature of coal and the methods of its formation are problems still unsolved. No satisfactory solution can be reached until we have obtained much more knowledge in regard to the original substance or substances from which it was formed, the conditions under which it was collected together, and the process of conversion of the original or mother substance into what is now known as coal.

The hypothesis, once so widely used, that all coals have been derived from the same mother substance, under the same or similar conditions, must be dismissed as unfruitful and even misleading. There is no doubt that the coal of each particular seam has its own peculiar properties, and these must be taken into account in any scientific theory of its origin. In spite of its attractive simplicity, we can no longer hold the "peat to anthracite" theory which has, in text books at any rate, held such long sway: so many of the facts accumulated in recent years cannot be explained or related by means of this theory.

Geologically, coal is a rock—a sedimentary rock. In some cases it has suffered little alteration, but in others there has been profound chemical change from the original woody fibre. It is often stated that coal consists mainly of hydrocarbons; this statement, however, cannot be said to rest on any chemical data, and is certainly not correct. It is true that, on destructive distillation, hydrocarbons are given off abundantly, but this *per se* does not prove that coal contains hydrocarbons ready formed; in fact it points to the contrary.

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* After Lockyer.

From the evidence that already exists, a chemist would say that coal contains little of hydrocarbons, beyond the methane and other volatile products which it gives off *in vacuo* at comparatively low temperatures. And he would add that the methods of chemical investigation are not yet sufficiently advanced to enable us to attack, with any prospect of great success, the problem "what is coal?" Nor is it likely that these problems will be solved by the geologist working alone. Problems of this nature demand the combined research of the geologist, the chemist, the botanist, and last but not least, the bacteriologist.

We do know that coal consists of the altered remains of vegetable growth which once flourished at various places on the earth. The plants and trees from which coal has been formed are apparently now extinct. The lignites and brown coals are of more recent origin and seem to have been derived from the remains and products of trees and shrubs, such as the ash and poplar, which still exist.

During the transition into coal, the woody fibre has not only lost hydrogen and oxygen, but has also become bituminised, so that, to the eye, most of the vegetable structure has disappeared.

Recent microscopic examination of coals has shown that they are not so homogeneous as they appear; also that they have been formed mainly of the droppings of trees and plants, in the form of spores, fruits, leaves and twigs. There is little evidence of any great amount of wood entering into their composition. The small proportion of wood actually found occurs mostly in the form of mineral charcoal or *mother of coal*, as it is called.

In all coals there is a certain amount of resinous matter, which forms very inflammable dust. In the hardest, purest and brightest coals, the material seems to have been reduced to a pulpy state before being subjected to pressure. Some parts, however, show the leaves, sporangia, megaspores and microspores of many different species of plants.

In some coals there are beautiful amber-coloured bodies of various shapes, to which Mr. Lomax has given the name *amberites*, while others contain oval bodies of a highly resinous nature, which he calls *ovalites resinosus*. Bands of a dull red colour can also be observed. The cannels differ so remarkably from bituminous (or humic) coals that it is supposed they were formed under very different conditions, namely, in inland lakes. Fish teeth and scales are sometimes found embedded in the upper portions of the seams.* The fact that cannel is found in actual contact with humic coal, in some seams, adds a further difficulty to the problem of the origin of coal.

When vegetable matter decays, in the absence of air, under water or in the earth, it undergoes a change somewhat similar to that which occurs when it is heated at a low temperature. Water, carbon dioxide and methane are given off, leaving a residue richer in carbon. Dr. Bergius, of Hanover, in a paper on the artificial production of coal, says he heated peat and cellulose with water to a temperature of 340° C. under 100 atmospheres pressure, and found that both were converted into a substance physically and chemically identical with coal. At 340° C. the process took 8 hours, while at 310° C. it took 60 hours. He estimates, that at the temperature of the earth's crust, it would take about eight million years to form coal.

The following table shows the change in chemical composition which occurs during the transition of woody fibre into the various kinds of coal.

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* J. Lomax, *Trans. Inst. M. E.*, vol. xlii., part 1.

It is interesting and instructive to regard coal, from a chemical point of view, as being substantially a condensation product of bodies of the cellulose class, derived from plants. There is, as the table below illustrates, an almost if not quite unbroken series of bodies, starting from wood and passing through peat, lignite and gas coals to anthracite, with progressive condensation, though it does not necessarily follow that these bodies have been in turn derived from one another.

	Carbon.	Hydrogen.	Oxygen and Nitrogen.
Woody fibre	50	6	44
Peat...	60	5·8	34·2
Lignite	66	5·2	28·8
Cannel or sapropelic coal	85·8	5·8	8·4
Bituminous or humic coal	88·4	5·6	6
Anthracite	94	3·4	2·6

The degree to which this process of condensation has been carried, can be determined roughly by distillation at red heat. The carbon, etc., removed (as gas) during this process is technically called the volatile matter, while that which remains is termed the fixed carbon. The further the condensation process has gone, the larger the proportion of fixed carbon found. The resistance of coals towards oxidising agents, such as nitric acid, increases with the condensation, being least with lignites and greatest with anthracites.

CONSTITUENTS OF COAL.

The many researches hitherto conducted on coal have failed to elucidate its chemical constitution, although they have yielded some information as to its mechanical structure. The problem has been attacked by five distinct methods, viz.:—

(i) Comparative analyses and examination of different varieties of coal (of different ages) together with wood and wood products;

(ii) Investigation of the decomposition products at different temperatures;
(iii) Investigation of the oxidation products at different temperatures;
(iv) The action of solvents;
(v) Micro-study of coal sections.

The evidence obtained so far goes to show that coal is an association of two or three distinct classes of substances, viz., (i) humus bodies, (ii) resinous bodies, and (iii) carbon residuum. Some writers add a fourth class hydrocarbon bodies; indeed there are some who state that coal consists mainly of hydrocarbons. The author has not, however, been able to find, up to now, any evidence of the existence of hydrocarbon bodies in coals, with the exception of occluded methane and in some cases a little ethane.

The results of micro-investigation have already been described; those obtained by means of the action of solvents will be considered later, as they are mainly confirmatory. Distillation and oxidation cannot be expected to yield direct results, for, since several (possibly many) substances are undergoing change simultaneously, the course of any individual reaction cannot be followed.

The evidence obtained from a comparative study of coals of different ages, and of wood products, is definite up to a certain point, but cannot, of course, lead by itself to an exact knowledge of the chemical structure.

Club mosses have spores which contain a yellow powder (lycopodium) that is exceedingly inflammable. Similar spores, from the vegetation of the carboniferous period, together with the more resinous portions of the pines, have resisted the forces which have been at work in the formation of coal through millions of years, and these spores remain but slightly changed in the coals.

In vegetable fibre, the two chief components are cellulose and lignose, which often are combined together as lignocelluloses. Both are carbohydrates, though in cellulose the percentage of carbon is rather less than in lignose.

There are also, in wood products, certain other classes of substances, *e.g.*, resins and essential oils. The essential oils absorb oxygen and are converted into resins, which are more stable and resist decay, thus accumulating in the coal substance. Such resins are found in considerable quantities in the lignites, cannels and bituminous coals.

The carbohydrates (cellulose, lignose, etc.), in the presence of air and water, become changed by decay into carbon dioxide and water. In the absence of air these ferment actions are retarded and carbon dioxide and methane are produced. In the conversion of vegetation into peat the chief factor is the growth of fungi and bacteria. Certain bodies known as *humic acid* and *ulmic acid* are produced, the composition of which is approximately

	C.	H.	O.	N.
Humic acid	60·1	4·7	31·5	3·6
Ulmic acid	62	4·6	33·3	—

These bodies, known as the *humus constituents*, are present in bituminous and other coals, associated with compounds called the *carbon residuum*; these latter compounds are much richer in carbon and have been formed from the humus bodies by progressive condensation. Together with these, there are the *resinous bodies* which have approximately the composition C, 79 per cent.; H, 10 per cent.; O, 11 per cent. Coals always contain a certain amount of water which appears to be held in loose chemical combination as it requires a higher temperature than 100° C. to remove it. The dried substance re-absorbs this amount of moisture on exposure to ordinary moist air. The greater the quantity of humus bodies in a coal, the more water it contains. Peats and lignites are distinguished by containing large quantities of moisture. Even after thorough air-drying they contain 15-20 per cent. of moisture which requires a temperature of 105°-110° C. to drive it off completely.

Analyses of cannel coals show that they contain practically nothing but resin bodies together with a small amount of humus bodies.

The calorific power of the three constituents, together with their approximate composition (assumed free from ash, sulphur and nitrogen) is as follows:—

	Calorific power. (Calories)	C.	H.	O.
Carbon residuum * ...	8670 — 8680	95·7	2·7	1·6
Humus bodies	6470 — 6490	63·0	5·0	32·0
Resin bodies	9120 — 9140	79·0	10·0	11·0

The characteristic properties of any particular variety of coal depend on the relative proportion in which these three groups are present in the conglomerate. Smokeless coals contain a high proportion of *carbon residuum*; this carries a high calorific power, partly because there is so little water contained in it. The *humus bodies*, distinguished by their high oxygen contents, carry much hygroscopic water. When heated they yield a large quantity of gaseous products and show no sign of melting; the residue does not cake. They begin to decompose at 300° C., water and tar distilling over. Up to 600° C. the gases are hydrogen, methane and carbon dioxide, with a small quantity of carbon monoxide. Humus bodies appear to be almost, if not quite, insoluble in pyridine.

The *resin bodies*, containing a medium amount of oxygen, no doubt form the cementing material in coal. They melt at about 300° C. and then decompose with evolution of hydrocarbons and oxygenated compounds. Soft coke is formed at 500° C., and on heating this to 1,000° C. hydrogen is evolved and a residue of hard coke obtained. There is little doubt that the coking qualities of a coal are dependent on the resin bodies contained in it. Some of the resin bodies are soluble in pyridine and some are not, but both classes apparently

* From American anthracite.

combine with this solvent. On exposure to air for a long period coking coals have their coking property diminished and some varieties lose it altogether.

THE ACTION OF SOLVENTS ON COAL.

Numerous attempts have been made to isolate definite compounds from coal by means of solvents, and many solvents have been tried.

Phenol extracts about 10 per cent. from some varieties of coal, and one or two workers have employed this solvent. Quite recently (1912), Fraser and Hoffman, of the U.S.A. Bureau of Mines issued a report on the products extracted from coal by phenol and then subjected to fractional crystallisation from other solvents. The composition of the phenol extract was as follows:—

	H.	C.	O.	S.	N.
Original coal	4·99	82·01	10·83	·55	1·62
Phenol extract	5·83	81·64	10·85	·38	1·30

Bedson, who has made a special study of this part of the subject, found that aniline dissolved a considerable quantity from some coals, and he was the first to describe (1899) the unusually great solvent action that pyridine has on many varieties. He found that Durham coal yielded up 16-18 per cent. to pyridine. Hutton seam coal yielded 20 per cent. to this solvent, and Bedson showed that, after the removal of this 20 per cent., the residue had lost its coking properties. The following table shows the composition of the two portions:—

	H.	C.	O.	N.	S.
Original coal	4·66	80·82	10·81	1·81	1·84
Residue	4·85	82·06	9·65	1·78	1·23
Pyridine extract	5·79	79·37	10·73	2·66	1·40

Further results published by Bedson in 1908 showed that in some cases the pyridine extract amounted to as much as the total so-called volatile matter. He found that the volatile matter of cannels varied very much in solubility and that the volatile matter in shales was insoluble in pyridine. The action of caustic soda was studied by Anderson and Roberts (1898). They found that the coking power was destroyed in some coals and weakened in others by extraction with this reagent. From their results they concluded that strongly coking coals contain, in addition to resin bodies, substances which are not soluble in alkali but which melt on heating and yield enough luting material to form coke.

Anderson and Henderson showed, in 1902, that the coking power of some Scotch coals was entirely destroyed by extraction with pyridine; with other varieties the coking power was considerably diminished. As regards volatile matter they give the following results from five different coals.

	1	2	3	4	5
Volatile matter in original coal...	31·9	39·8	46·5	27·4	36·7
Volatile matter in residue, insoluble in pyridine ...	39·2	44·1	49·1	29·6	43·0

These results indicate either that the pyridine treatment alters the coal residue or that the solvent combines with this residue to form substances which are volatile or are decomposed on heating, with formation of the so-called volatile matter.

Working on a Durham coal, V. B. Lewes obtained the following results (calculated on material free from moisture and ash):—

	H.	C.	O.	N.	S.	Fixed.	Volatile
Original Coal ...	5·57	82·87	8·72	1·68	1·16	63·00	37·00
Residue	4·71	79·15	14·00	2·14	—*	64·46	35·54
Pyridine extract...	7·18	81·04	7·98	3·80	—*	—*	—*

* Not estimated.

The above results indicate that extraction by pyridine does not decrease the total volatile matter in the residue to the degree expected; in fact there is, in some instances, more volatile matter in the extracted residue than in the original coal.

The increase in nitrogen in the residue and extracts points to a combination of pyridine with the extracted portion, and also with some constituent in the residue.

Though not wholly conclusive the evidence obtained by means of solvents goes to show that coking coals and cannels contain two distinct kinds of resins, viz.:

(1) Resins soluble in pyridine, saponifiable by alkali and easily oxidised to humus bodies with evolution of water and carbon dioxide. Possibly it is these bodies which initiate spontaneous combustion in coal.

(2) Resinous (?) substances not saponifiable by alkali and insoluble in pyridine although they combine with it.

Both these classes of substances melt at about 300° C. with production of luting materials, which, with the charred products from the other constituents, form coke. At a higher temperature the molten material decomposes and the solid residue becomes harder as the temperature increases. In the first stage of the decomposition tar and other hydrocarbons are given off, but in the later stages nothing but hydrogen is evolved.

The mode of combination of the nitrogen in coal is not known. In English coals the average amount of nitrogen is 1·4 per cent. which is equivalent to about 148 lbs. of ammonium sulphate per ton of coal. The actual yield obtained in the manufacture of coal gas and coke is only 13-22 per cent. of the theoretical; most of the nitrogen remains behind in the coke, but in what form is unknown. If a current of hydrogen is passed over hot coke, ammonia is generated, but no other gas has been found to effect the production of ammonia from coke. This indicates that the nitrogen in it is probably present as a nitride, cyanide, or cyanamide.

GASES IN COAL.

Most coal seams contain fire-damp, and some contain very large quantities of it. Fire-damp is a mixture of gases, the chief constituent, methane, being accompanied by varying amounts of carbon dioxide, nitrogen, and sometimes olefiant gas, sulphuretted hydrogen and hydrogen in small quantities. Sometimes higher hydrocarbons of the paraffin series are detected, and in hot mines carbon monoxide appears to be a constant constituent, though in very small amount. There is often a considerable quantity of nitrogen, as is illustrated by the following analyses of gas from Hutton pit:—

	Hutton Main. 100 fathoms.	Hutton Main. 175 fathoms.
Methane	50	50
Air	23	6
Nitrogen (in excess of that in air) ...	27	44

Three per cent. of hydrogen was reported by Playfair in some gas from Low Main, Jarrow, and 6·5 and 1·9 per cent. olefiant gas by Bischoff in mines at Wellesweiler and Gerhardt. Abel found ethylene in the gas at Garswood Hall, and ethane has been found by Dr. Wheeler in fire-damp from the Bellevue mine, Alberta, Canada.

In many seams the gas evolved contains over 95 per cent. of methane. The following table gives the results of accurate analyses carried out by MM. Mouren and Lepape* on fire-damp from various mines.

It is remarkable that the ratio of helium to nitrogen in the gas from Mons is over 23,000 times as great as the corresponding ratio in air.

Fire-damp exists in some coal seams under enormous pressures; measurements made have shown pressures of 200, 460, 430, and 318 lbs. per square inch. Pockets or small caverns occur in some seams, and these are naturally filled with fire-damp (occasionally mixed with powdered coal), sometimes under very great pressure. When these are tapped there are violent outbursts of gas. Such outbursts or *blowers* are by no means rare and as the mines get deeper and more extended their number seems to increase.

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* *Colliery Guardian*, November 1, 1912.

Locality.	CH_4	CO_2.	N_2.	Ar. and traces of Kr. and Xe	He and traces of Ne.	Total "rare" gases.
Liévin	97·00	0·5	2·41	·04	·013	·053
Anzin	97·92	0·16	1·854	·02	·044	·065
Lens	98·15	nil.	1·81	·03	·0003	·037
Mons	99·60	traces.	0·317	·003	·050	·053
Frankenholz ...	95·09	2·8	2·06	·021	·027	·048

Blowers vary very much in magnitude and in the force of the escaping gas; sometimes they cause tons of coal to be projected into the workings.* Cases are on record in which millions of cubic feet of gas have been liberated by one blower,† and a blower has been known to supply enough gas to light the surface workings of a pit for years.

It has not yet been definitely established how methane comes to be formed in these seams. Its occurrence is not peculiar to coal mines for it is found in many shale mines, metalliferous mines and salt mines, and in enormous quantities, mixed with other gases, in the natural gas deposits in America, Russia and other countries. Also it is formed when vegetable matter decays under water.

The occurrence in coal of such large quantities of methane practically free from other hydrocarbons is, from a purely chemical point of view, very mysterious. Among the thousands of organic compounds which have been made in the laboratory, not one is known which spontaneously decomposes with the evolution of methane. Furthermore, no process is known (with the exception of the reactions between zinc methyl or aluminium carbide and water) by which methane, unmixed with other hydrocarbons or with hydrogen, can be prepared in the laboratory. For these and other reasons the author thinks it necessary to conclude, *on purely chemical grounds*, that the formation of methane in coal seams is due to bacterial, fermentation or enzyme action.

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* One at Valleyfield Colliery, March 9th, 1911, killed three men; they were buried under the coal blown out.

† H. Stokes at the Royal Commission gave evidence that one blower yielded 5,000,000 cubic feet of gas in three days, and another 1,000 cubic feet per minute for over a week.

That such action has been the chief factor in the conversion of the plant *débris* into a pulpy and almost structureless form is almost certain. We know that leaves and other vegetable products, when they decay in absence of air, ferment and give off marsh gas and carbon dioxide. We also know, from many observers, that some coals continue to give off marsh gas for months after they have been mined. There is good reason to think that both these processes are due to the action of bacteria and ferments. Possibly the chief factor in the transition from decaying vegetation to anthracite is a constant fermentation. At the present time most geologists accept the bacterial theory for the first stage in the transition from vegetable matter to coal. Bernard Renault proved the existence of micrococci in the petrified state in some coals; he showed also that the tissues in some petrifactions show all the phenomena of cells attacked by bacteria.

E. Galle* found, in the course of a bacterial study of different kinds of coal under both anaerobic and aerobic conditions, that, out of seven kinds of bacteria isolated, four, when grown on suitable media in presence of coal, produced combustible gas mixtures containing from 71·5 to 84·8 per cent of methane and from 5·4 to 27·3 per cent. of carbon dioxide. He showed that these combustible gas mixtures were generated by the bacteria even under conditions approaching those which prevail in nature.

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* E. Galle, *Central Bakter a Parasitenk*, 1910, 28, 461-473; *Chem. Zeit.*, 1911, i. 48.

If such bacterial action takes place in the formation of coal, and the degree of condensation is commensurate with the amount of fermentation, then according to most theories it would be expected that anthracite seams would possess the greatest relative amount of fire-damp, and steam coals more than gas coals. But the reverse is generally the case. Hence if the gas was formed it must have escaped during or after its generation.

It may be that the escape of this gas was one of the chief factors in the formation of anthracites and steam coals, and that in seams where the gas could not get away the transition was arrested and the bituminous or the cannel coals are the result.

There is little doubt that the mother substance of the coals was deposited in almost horizontal layers or sheets, with at most only a slight dip. It is due in all probability to subsequent earth movements that the coal beds, as found in England and Wales, are confined to much smaller areas. By these earth movements the mother substance was transferred from some parts, which thus became *denuded*, and collected in "basins."

That the regions of the present English and Welsh coalfields were subjected to great earth movements and creeps is shown by the variety of dip in the various seams, by the folding of the rocks and by the numerous faults. The enormous pressure, caused by these movements, may have had a great influence in the process of transition of the pulpy vegetable products, formed by the bacteria, ferments, etc., into coals of the humic and anthracitic kinds. The escape of the gas, however, would be a much more important factor, and it is perhaps possible that these movements allowed the gas to escape from some seams and not from others.

GAS OCCLUDED BY COAL AND COAL-DUST.

Coal, like charcoal, has the power of condensing or occluding gases. That this is so can be proved by placing any sample of coal or coal-dust *in vacuo*; gases are evolved and can be collected and examined. From freshly-mined coal a considerable quantity of methane is evolved: most of this passes into the air of the return airways and so out of the mine.

The following table* shows the difference between the gases contained in some freshly-mined coal and in the same coal after long exposure to air.

	Freshly-hewn Coal.	Same after Exposure to Air.
CO_2	1·6	1·18
O_2	8·8	23·8
CH_4	44·6	3·5
N_2	44·7	71·4

The following tables,† which show the gases in the coal and mine dusts of the Busty Seam at Birtley, Durham, are of great interest. It will be seen that, while the fresh coal contains a large quantity of gas rich in methane, the old dust from the timbers contains relatively little gas, with quite a small percentage of methane.

It should be mentioned that coal after removal from the seam not only loses some of its methane, either mechanically or by oxidation, but also takes up gases from the air, oxygen being occluded by it rather more readily than nitrogen.

The combustible gas from the bright coal and dant seems to be chiefly, if not entirely, marsh gas, whilst that from the screen dust and dust from the timbers gives, on combustion, figures which indicate the simultaneous presence of hydrocarbons of higher carbon contents than marsh gas.

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* Bedson, *Trans. Fed. Inst. Min. Eng.*, Aug. 1902.

† Troubridge, *J. S. C. I.*, Dec. 1906.

GASES IN COAL AND CERTAIN COAL DUSTS FROM BUSTY SEAM AT BIRTLEY, DURHAM.

	Bright coal.			Dant.*			Surface dust.			Dust from Timbers.		
Weight of coal ...	296 grams.			246 grams.			156 grams.			201 grams.		
Last portion of air (*A*) ...	22·0 cc.			30·4 cc.			11·1 cc.			17·4 cc.		
Gas at ordinary temperature (*B*)	63·1 cc.			35·6 cc.			8·5 cc.			2·9 cc.		
Time of standing ...	16 days.			167 hours.			7 days.			?		
Gas @ 100° C. (*C*)	414 cc.			86 cc.			14·25 cc.			22·67 cc.		
Time of heating ...	68 hours.			?			?			?		
Volume gas per 100 grams. coal @ 100° C. ...	139 cc.			35 cc.			9·2 cc.			11·4 cc.		
	A.	B.	C.	A.	B.	C.	A.	B.	C.	A.	B.	C.
CO_2	3·0	7·0	4·0	2·9	17·1	35·8	3·0	4·0	55·8	5·6	4·7	85·1
O_2	22·5	3·2	·3	25·1	10·8	·6	23·5	8·5	2·6	19·4	13·7	2·9
CO	—	·7	·8	—	—	1·5	—	—	4·2	1·7	1·5	—
Olefines ...	—	—	—	—	—	—	—		—	—	—	—†
Paraffins ...	16·1	53·4	93·9	3·1	9·7	60·5	4·7	2·6	22·5	1·9	2·2	1·8
Nitrogen ...	58·4	35·7	1·0	68·9	62·7	1·6	68·8	84·9	14·9	71·7	79·4	9·8
Analysis of the coal and dusts.												
Moisture ...	0·63			1·09			0·81			3·07		
Volatile matter ...	31·47			15·2			28·4			22·33		
Fixed carbon ...	64·12			75·41			61·82			29·01		
Ash ...	3·78			8·3			8·97			45·59		

These results are of great importance and seem to indicate (which has not been previously pointed out) that coal-dust, in the presence of air, probably causes the occluded gases to combine by partial oxidation, the methane giving higher homologues.*

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* "Dant" is the North of England term for the black substance called mineral charcoal or mother of coal.

† — indicates nil.

$$\begin{matrix}CH_4\\CH_4\end{matrix} + O = \begin{matrix}CH_3\\|\\CH_3\end{matrix} + H_2O$$

Methane. Ethane.

The occurrence of hydrocarbons of higher carbon contents than methane, in certain dusts, has also been described by Bedson in screen dusts at Ryhope, and attention has been called to the same thing in the report of the Austrian Fire-damp Commission. Bedson has also examined gases from coal and dusts from Fernie mine, British Columbia, where an explosion occurred in 1902.

GASES FROM FERNIE COAL DUST AND COAL.

—	Volume from 100 grs.	Per cent. CO_2	Per cent. O_2	Per cent. C_nH_{2n}	Per cent. CO	Per cent. C_nH_{2n+2}	Per cent. N_2
Coal dust—	c.c.						
(*a*) Gas at ordinary temperature	12·8	25·5	9·7	Nil.	Nil.	5·3	59·5
(*b*) Gas at 100° C. ...	16·2	36·7	11·7	Nil.	Nil.	10·8	40·6
Coal—							
(*c*) Last portion of air	—	7·5	10·6	Nil.	Nil.	8·6	73·3
(*d*) Gas at ordinary temperature	22·2	16·5	7·2	Nil.	0·9	24·3	57·1
(*e*) Gas at 100° C. ...	23·1	35·4	1·0	0·4	7·9	52·7	2·6

The result of the combustion of these gases gave the following values for n in the formula C_nH_{2n-2}; in (*a*) $n=1$; in (*b*) $n=4·4$; in (*c*) $n=2·1$; in (*d*) $n=1·8$; in (*e*) $n=2·5$.

The quantity and quality of occluded gas in coal dust is of great importance, as such gas (in the occluded condition) is much more chemically active than the same gas when free and independent of solid surfaces; it is comparable to gas under great pressure, a fact that should be carefully noted.

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* This problem is being investigated by the author. The results at present point to the higher hydrocarbons being formed by oxidation of the coal substance and not the methane.

There are many practical mining people who suppose that, in a coal-dust and air explosion, an explosive mixture of gas and air is first formed by distillation of volatile products from the dust. Such a supposition is neither necessary nor desirable. The gas and volatile products are much more chemically active when condensed or occluded in the dust than they are when in the free gaseous condition—a fact that is well known to chemists.

CHAPTER II.

COMBUSTION.

Many substances have the power to unite spontaneously with oxygen, energy being liberated during the change. The action may take place rapidly, heat being generated at such a rate that the substance itself (or some of the resulting products) is raised to a temperature at which it gives out light: when this happens the change is called a *combustion* (or a rapid combustion) and the substance is said to be combustible. Or the action may proceed so slowly that the heat is dissipated almost as rapidly as it is set free and the temperature does not rise appreciably above that of surrounding bodies: in such a case the change is called *slow oxidation.*

But whether the action is rapid or slow, in the case of any given substance, if the final products are the same, the quantity of heat liberated per unit weight of the substance is always constant. This quantity is called the *heat of combustion* or the *calorific power.*

The final products are not invariably the same: thus when iron is burnt in oxygen an almost black compound, triferric tetroxide Fe_3O_4, is obtained, whereas when iron rusts in ordinary air the product is hydrated ferric oxide $Fe_2O_3H_2O$. And even when the final products are identical it does not necessarily follow that, except for the difference in speed, the course of the reaction is the same. Coal can absorb oxygen at a low temperature with production of some organic compound richer in oxygen (said to be humic acid). At a moderate temperature — below 100° C. — it absorbs oxygen, giving water, carbon dioxide and other products, but unless the temperature approaches 350° C. there is no indication of burning. At and above that temperature, varying with the quality of the coal, rapid combination takes place and the coal burns.

IGNITION TEMPERATURE.

In order that a given combustible substance may begin to burn, *i.e.*, to combine so rapidly with oxygen that light is produced, it is usually necessary to heat some part of the substance until it reaches a certain temperature, which is called the *temperature of ignition.* For a given pressure of oxygen this temperature of ignition is constant for any particular substance, provided that the substance, if solid or liquid, is not in a finely divided state. The influence of increasing the surface to a high degree, as happens when a solid is finely powdered, is illustrated by the case of iron; pyrophoric iron, an impalpable powder obtained by reduction of iron oxalate in hydrogen, ignites when shaken into air at the ordinary temperature, whereas lump iron does not burn until white heat is reached.

Under ordinary conditions the range of ignition temperature for different substances is very wide. Phosphoretted hydrogen and zinc ethyl take fire in air at the ordinary temperature, phosphorus inflames at 60° C., and carbon bisulphide at 150° C., whereas nitrogen will not burn below about 3,000° C.

In the case of gaseous mixtures it is found that the ignition temperature varies considerably with the diameter and nature of the interior walls of the containing vessel, so the results are only approximate.

The following table* shows the temperature of ignition of various gases mixed with the equivalent quantity of oxygen for complete combustion.

TEMPERATURE OF IGNITION.

Gas.	Current of Gas.	Gas in Closed Tubes.
Hydrogen	650°–730° C.	530°–606° C.
Methane	650°–730° C.	606°–650° C.
Ethane	606°–650° C.	530°–606° C.
Ethylene	606°–650° C.	530°–606° C.
Carbon monoxide	650°–730° C.	650°–730° C.
Sulphuretted hydrogen ...	315°–320° C.	250°–270° C.

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* After F. Clowes.

Probably the most reliable temperatures of ignition of gaseous mixtures are those determined by Dixon and Coward,* who eliminated the influence of the walls of the vessel to a great extent by heating up the air (or oxygen) and the combustible gas separately before mixing. They give the following figures:—

	In Air.	In Oxygen.
Hydrogen	580°–590° C.	580°–590° C.
Carbon monoxide	644°–658° C.	637°–658° C.
Acetylene	406°–440° C.	416°–440° C.
Methane	650°–750° C.	556°–700° C.
Ethylene	542°–547° C.	500°–519° C.
Cyanogen	850°–862° C.	803°–818° C.

In a homologous series of hydrocarbons the temperature of ignition appears to fall as the molecular weight increases.

Methane and oxygen	556°–700° C.
Ethane ,, ...	520°–630° C.
Propane ,, ...	490°–570° C.

Mallard and Le Chatèlier give the following figures:—

2 vols. hydrogen, 1 vol. oxygen	550°–570° C.
1 vol. ,, 2 vols. ,, ...	530° C.
1 vol. air, 2 vols. hydrogen	530°–570° C.
2 vols. ,, 1 vol. ,, ...	550° C.
2 vols. oxygen, 1 vol. methane ...	650° C. (Explosion). 600° C. (Slow combustion).
1 vol. oxygen, 2 vols. methane	650°–660° C.
1 vol. methane, 9 vols. air ... below	750° C.

They point out that it is remarkable how the ignition temperature of detonating mixtures is only slightly modified by the introduction of even a considerable volume of inert gas; this is so, at least, as long as the limits at which the mixture ceases to burn are not approached too closely.

The addition of an equal volume of carbon dioxide has a greater influence on the ignition of carbon monoxide than on that of hydrogen, which indicates that the products of combustion may have a special restraining influence.

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* Dixon and Coward, *Trans. Chem. Soc.*, 1909, 95, 514.

Very important differences exist between the times required to ignite different gaseous mixtures when heated to the ignition temperature. A mixture containing hydrogen or carbon monoxide ignites immediately, whereas methane mixed with air or oxygen takes quite a perceptible time, which in some observations amounted to as much as ten seconds.

An explosive mixture of hydrogen or ethylene with air can be ignited by a red-hot poker, but one of methane and air cannot be ignited in this way nor even by a bright red-hot piece of charcoal.

Not much is known yet as to the influence of pressure on the temperature of ignition. According to Mitscherlich, a mixture of hydrogen and oxygen in the proportion two to one by volume is more easily inflamed at low pressures than at high—a result not easy to explain, as the reverse would be expected. The figures he gives are 620° C. at 760 m.m. pressure and 540° C. at 360 m.m.

Calorific Power.

It has already been stated that, provided the final product is the same, unit weight of any given combustible combining with oxygen always evolves a definite amount of heat, whether combustion is rapid or slow, and whether it occurs in oxygen or in air; this quantity of heat is called its *calorific power*. Thus one pound of hydrogen when burnt to water either in oxygen or in air always yields 29,300 units of heat, *i.e.*, enough heat to raise the temperature of 29,300 lbs. of water from 0° C. to 1° C.

The following table gives the calorific power of various substances.

	Units (Calories).
Hydrogen	29,300
Rape oil	13,600
Carbon monoxide	2,400
Charcoal	8,080
Good bituminous coal	7,050
Dry wood	3,600
Wood with 20 per cent. moisture ...	2,700
Peat	2,500-3,000

Calorific Intensity.

But although the quantity of heat liberated by the combustion of a unit weight of a substance is constant, the temperature attained during combustion varies greatly with the conditions. If an inert gas (including excess of combustible gas or of oxygen) is present, much of the heat will be used up in raising its temperature, and so the intensity of heat will not be so great as that obtained in the absence of inert gases.

The highest temperature that can be obtained by burning a given combustible in air is called the *calorific intensity* of that substance in air; under specified conditions it is constant for that substance.

The same combustible burning in air containing more oxygen than the normal amount or in pure oxygen gives a higher temperature, *i.e.*, a greater calorific intensity. The result of withdrawing the inert gas, nitrogen in this case, is well illustrated by the combustion of iron. Iron at bright red heat will not burn in air but burns in oxygen, a property which is utilised in the cutting of iron plates and girders. A portion of the mass of iron to be cut is heated to bright redness by means of an oxy-coal-gas flame. On shutting off the coal-gas the iron proceeds to burn in the oxygen jet and the heat of combustion melts the adjacent metal; by suitably directing the jet of oxygen, the mass can be cut or melted into two parts. If a current of air were used the calorific intensity would fall below the ignition temperature and combustion would cease.

The intensity of the heat and pressure of combustion, especially in gaseous mixtures, falls short of the calculated figures by a very considerable amount. This difference, which has not yet been fully explained, is due to several causes, viz.:

(i) The marked increase in the specific heats of steam and carbon dioxide as the temperature rises.

(ii) Ordinary gaseous explosions (excluding detonations) are not instantaneous; some combustion goes on during the cooling period.

(iii) Energy is lost by direct radiation: this loss amounts to 15-20 per cent.

(iv) Dissociation of the products. There is little evidence that this is an important factor in the case of *detonations* of gaseous mixtures, but it may play a considerable part in ordinary explosions and gaseous combustions, especially in presence of solid surfaces.

It is a curious and very important fact that the temperature attained in detonations is often far above the temperature of dissociation of the products of combustion. Such dissociations have, however, all been carried out in vessels where the surface of the walls must have exerted a considerable influence.

Limits of Ignitability of Gas Mixtures.

A mixture of combustible gases with air or oxygen will not burn when the relative proportion of one of its constituents falls below a certain value. For example, three volumes of electrolytic gas (containing two volumes of hydrogen and one volume of oxygen) will not unite when mixed with 27 volumes of oxygen, or with 24 volumes of hydrogen. Three volumes of electrolytic gas are rendered non-inflammable also, by diluting with 18 volumes of nitrogen, 12 of carbon dioxide, 9 of carbon monoxide, 6 of ammonia or 24 of water vapour (above 100° C).

A mixture of methane and air only gives complete combustion when there are $9\frac{1}{2}$ volumes of air to one volume of methane. It will not burn at all when the air exceeds 17-20 volumes, or is less than $6\frac{3}{4}$ volumes for one of methane. In the determination of these values an electric spark was used as the source of ignition.

The following table shows the limits of composition for ignition to occur, in the case of various combustible gases, with the given source of ignition, in this case a spark obtained from an induction coil.

PERCENTAGE OF GAS MIXED WITH AIR.

Gas.	Lower Limit.	Upper Limit.
	Per cent.	Per cent.
Hydrogen	5	72
Methane	4½–5½	13–14
Carbon monoxide ..	13	75
Ethylene	4	22
Acetylene	3	82
Water gas	9	55
Coal gas	5	28

The limits vary greatly according to the source of ignition and also the mass of the hot body causing it. With the flame of a safety lamp the limits are narrower than those given above the lower limit being a higher percentage of gas and the upper limit a lower percentage of gas, while with a spark from a coil fitted with a condenser or an electrolytic interrupter the limits are wider.*

These limits may also be influenced by the initial temperature and pressure of the gas mixtures, but the observations made by different investigators on these points are contradictory.

As a general rule, for the propagation of combustion in a gaseous mixture *it is necessary that the heat liberated by the ignition of the first portion should be sufficient to reproduce this temperature of combustion in the adjacent portions.*

EXTINCTION OF FLAMES IN ENCLOSED VOLUMES OF AIR.

A candle burning in an enclosed space of air continues to burn, forming carbon dioxide and water, until the oxygen has been reduced from 20·9 to 17 per cent.: when this point is reached the flame goes out. Other combustibles such as petroleum, ligroin, benzene, etc., behave in a similar way, and for each of them there is a definite composition of atmosphere at which the flame dies out. The flames of all ordinary liquid and solid combustibles are extinguished long before half of the oxygen has been consumed.

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* Prof. Thornton in a paper read to the British Association, 1912, gives the limits for methane as 4½% and 14%, and for coal gas 6% and 40%, using momentary electric arcs with either direct or alternating currents. It appears, however, that the methane used was made from sodium acetate. This method yields very impure gas, containing sometimes as much as 10% hydrogen: it also contains other hydrocarbons, so that the limits given here for methane are not reliable.

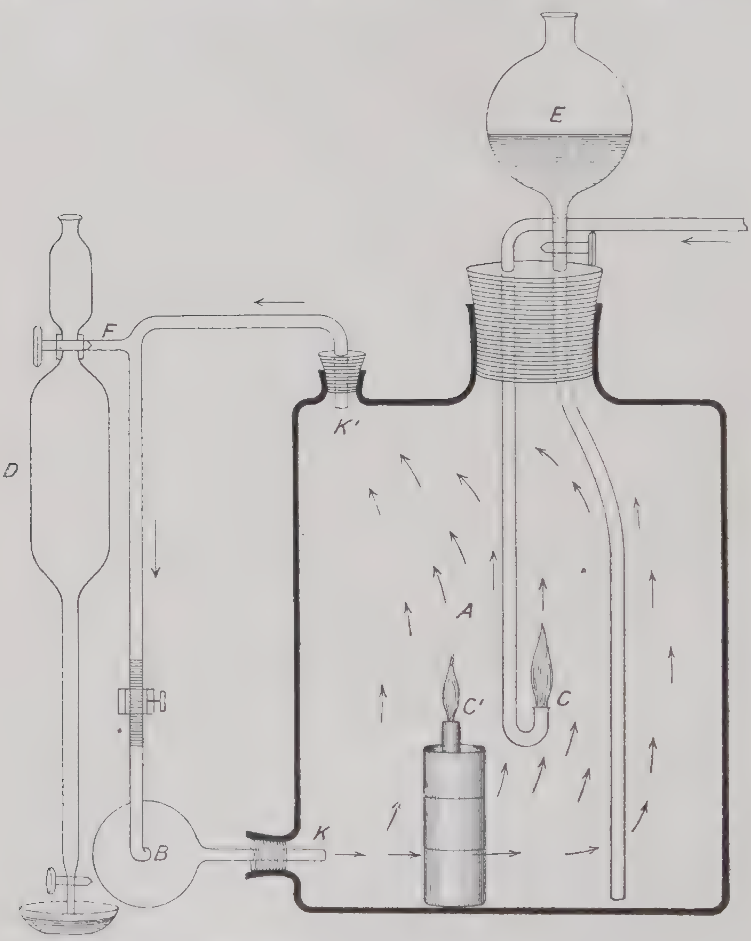
Most gases, however, reduce the percentage of oxygen to a much lower figure, as is seen from the following table; but one gas—methane,—which is of such vital importance in mines, is fortunately extremely sensitive to lack of oxygen. A methane flame goes out when the oxygen has been reduced to about 17½ per cent.

PERCENTAGE OF OXYGEN AT WHICH VARIOUS FLAMES ARE EXTINGUISHED.

Combustible	Percentage of Oxygen.
Soft candle	16·9–17
Petroleum	16·9
Ligroin (B.P. 90° 120° C.) ...	16·9
Petroleum ether	15·5
Benzene	16·4
Hydrogen	7·5
Acetylene	9·5
Methane	17·5
Coal gas (Liverpool)	11·5

The apparatus used in determining the composition of air at which various flames are extinguished consists of a large glass gas holder A, provided with several openings KK¹ through which air is circulated by an electrically-driven blower B.

The gas flame on trial is shown at C or, in the case of a liquid or solid combustible, at C¹. The flame burns until it has used up some of the oxygen and created an atmosphere in which it can no longer burn. The air is circulated all the time by the blower B, so that the flame is not put out by any merely local collection of air poor in oxygen, as is found to be the case when a closed vessel, without means of circulating the air, is used.* Immediately after the flame goes out a sample of the gas is withdrawn into the apparatus



Apparatus for Determining Composition of Air at which Flames go out.

D, water from E being run into the gas holder to replace the gas taken out for analysis.

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* This circulation is necessary to get concordant and correct results. The figures given by earlier investigators, F. Clowes and others, are not correct because this was omitted.

By this arrangement several samples of gas from one experiment may be obtained, and samples may also be taken at different times during the progress of an experiment.

The flames of solids and liquids, burning in a limited supply of air, decrease in size and illuminating power as the percentage of oxygen falls. In air containing more than 17½ per cent. oxygen it is possible, with a little practice, to estimate the percentage of oxygen by the luminosity and height of a candle flame.

On the other hand flames of gases increase in size as the amount of oxygen diminishes and, in the case of acetylene, sulphuretted hydrogen, marsh gas and possibly some other gases, the flame actually leaves the jet some considerable time before it goes out. It is curiously interesting to watch acetylene burning from a jet in a large closed vessel. When the diminution of oxygen has reached a certain point and the oxygen left tests about 11 per cent., the flame, a double hollow cone, rises from the jet and continues to burn several inches above it, moving gently up and down as if it were alive and seeking more congenial surroundings. It continues to behave in this manner until the percentage of oxygen has been reduced to 9½ when it goes out. This will-of-the-wisp phenomenon is shown equally well by burning sulphuretted hydrogen and also to a less extent by methane; in this last case the flame goes out very soon after leaving the jet.

This phenomenon of the flame leaving the jet can be seen to a slight extent in an ordinary oil lamp. When the flame is turned down so as to become blue (the procedure adopted when testing for fire-damp in a mine) it can be clearly seen that the small blue flame is separated from the wick by a distinct space, amounting to over ⅛ inch, in which no doubt the mixing of vapour and air is taking place.

CHAPTER III.

RUSTING, SLOW OXIDATION OR AUTOXIDATION.

Many substances that burn in oxygen will react with it below the temperature of ignition: several metals and many organic materials behave in this way. In the case of metals the process is called rusting, and more generally such oxidation is termed slow combustion or slow oxidation.

Among the organic substances which are oxidised at moderately low temperatures, coal is one of special interest. Some varieties of coal absorb oxygen at the ordinary temperature quite perceptibly and rapidly when in a finely divided state. The rate of absorption of oxygen increases greatly as the temperature rises. Very little if any carbon dioxide is given off at first and not much heat is evolved. It is said that the product formed during this absorption is humic acid.

Some heat is, however, given off during this slow oxidation, and if the coal is in a warm place and in the state of slack or finer powder, to which the air has access, it may heat up. When hotter it absorbs oxygen still more quickly, which in turn causes more heat to be generated; the temperature of the coal increases as it were by compound interest. This absorption of oxygen often causes spontaneous combustion in coal mines and heaps of coal.

Spontaneous ignitions of a similar nature sometimes occur in heaps of oily rags and in haystacks. The spontaneous combustion of coal will be considered in detail later.

THE INFLUENCE OF CATALYSTS ON COMBUSTION.

There are certain materials which have the power of making combustible gas mixtures react rapidly at temperatures far below their ordinary ignition points. A mixture of hydrogen and oxygen or air, for example, has an ignition temperature of about 1,200° F., but if passed over finely divided palladium, warmed to 140° F., combination takes place rapidly.

Other materials such as finely divided platinum, nickel, oxide of nickel, oxide of iron, and even fire-clay possess this property, though to a smaller degree than palladium. Such materials are called *catalysts*: they have a profound influence on the rate of chemical change yet they themselves suffer no appreciable alteration: with certain precautions as to purity and temperature they can cause the combustion to proceed for an indefinitely long time.

Their influence is not confined to the combustion of hydrogen. Hydrocarbons and many other substances are similarly affected, though for the combination of these the catalyst must be at a higher temperature than in the case of hydrogen.

The palladium (or other catalyst) is just the same at the end of the combustion as at the beginning and the mechanism of its action is still very obscure. Combination of oxygen and hydrogen alone (*i.e.*, in the absence of a catalyst) at 140° F. is so slow that it would take years to form any measurable amount of water; indeed there is no direct evidence that any water is formed at this temperature. But, reasoning from analogy, physical chemists believe that combination does occur, though with extreme slowness, and they define a catalyst as a body which alters the rate of chemical change in a given reaction. The alteration may be either an acceleration or a retardation. In the latter case the catalyst is said to act negatively.

This process of catalysis is not confined to oxidation but is very general in all classes of chemical reactions. There is a class of soluble organic compounds, called enzymes or unorganised ferments, that resemble the above mentioned catalysts, in the fact that quite a small amount of them can cause chemical change to proceed throughout a very large mass of reactive material. And certain colloidal solutions of metals such as gold and platinum produce effects so similar to those caused by enzymes that they have been called "inorganic ferments."

The activity of enzymes and colloid metals increases with temperature up to a certain point, after which, if the temperature is raised still higher, their activity begins to diminish, *i.e.*, in the case of these catalysts an *optimum temperature* is attained. In this respect they differ from the insoluble inorganic catalysts (such as finely divided palladium), for these have no optimum temperature above which their activity is destroyed.

SURFACE OR FLAMELESS COMBUSTION.

The action of catalysts on combustion can have other effects than that of altering the velocity, for by means of them it is possible to burn large quantities of gas rapidly and without flame.

When a mixture of methane and hydrogen is burnt in the ordinary way the methane burns twenty times as fast as the hydrogen, but if this mixture is burnt in contact with a mass of solid material exposing a large surface, such as firebrick, the hydrogen burns more rapidly than the methane and there is no flame. This method of combination, known technically as surface or flameless combustion, has been studied by various scientists from time to time.

Sir H. Davy in 1817 was the first to record that hydrogen, carbon monoxide and several volatile organic compounds, when mixed with air, would burn if brought into contact with platinum at a temperature below visible redness. Later he found that finely divided platinum, when damped with spirits of wine, became red hot on exposure to air, the heat being due to the oxidation of the spirit.

Dulong and Thénard in 1823 discovered that many other substances had the property of inducing combustion below the ignition temperature; they found that this property was possessed not only by metals such as osmium, gold, silver and nickel but also by such different materials as pumice, porcelain and rock crystal.

In recent years Bone has applied the principle of surface combustion on a technical scale and has shown that by means of it great efficiency can be obtained in steam raising. With gas firing, half a per cent. excess of oxygen is all that is required in order to get perfect combustion without a trace of carbon monoxide, and as much as 93 per cent. of the heat can be transferred to the boiler water.

A special boiler is used with tubes 3 feet long passing through it. These tubes are packed with nodules specially made from porous fire-clay, and the mixture of gas and air, in the correct proportion, is passed through them at sufficient pressure and speed to prevent the flame striking back. At the start the mixture is lighted at the exit end of the tubes; as the fire-clay gradually becomes hot the flames shoot back into the tubes and the combustion takes place, without flame, on the surface of the fire-clay.

It is not only gaseous fuel which can be made, by means of catalysts, to burn at a lower temperature and with increased speed. The author has found that liquid and solid combustibles, when in contact with a suitable catalyst, will burn in air at temperatures much below their ignition points. Organic matter of the nature of peat has a fairly high ignition temperature, but it has been found that when intimately mixed with oxide of iron, as in bog iron ore, it will burn at 200° C.; also tobacco smoke or flue smoke, when passed over heated oxide of iron at about 200° C. is completely burnt.

Most combustibles such as a candle, coal, wood, etc., will not burn at the ordinary temperature in air that contains less than 17 per cent. of oxygen. In fact even at

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[*] Bone, *J. S. C. I.*, *1910*, 1138, 1448 ; *1911*, 406, 527 ; *1912*, 62.

high temperatures it is not possible to get complete combustion of the oxygen without excess of unburnt combustible gases. In many boiler installations the volume of free oxygen left in the flue gases is very considerable, sometimes amounting to 17 per cent.

Even in carefully tended fires, that are mechanically stoked and are fed with fuel of good quality, there is seldom less than 6 per cent. of free oxygen although combustible gas and smoke are simultaneously present with it in the flue gas. This is because, with such a low percentage of oxygen, the combustible matter is below its ignition point.

The author has found that gas and smoke escaping in this way can be burnt completely if the flue gases, while still hot, are passed over a catalytic material—such as bog iron ore (preferably titaniferous bog iron ore).

By means of this or some similar process complete combustion can be effected; all the heat of combustion can be obtained and, what is perhaps of even greater importance, the nuisance of smoky chimneys can be entirely eliminated. Flue gases treated in this manner are entirely free from carbon monoxide, hydrocarbons and unburnt smoke, and, after removal of dust and sulphur dioxide, can be used for reducing the oxygen percentage in mines to guard against explosions and gob-fires.

Bone* is of opinion that his work proves that "catalytic combustion" depends primarily upon the condensation or absorption of one or other (possibly both) of the reacting gases by the surface, whereby they are rendered active. He finds that the catalysing power of a new surface at a given temperature usually increases up to a steady maximum when successive charges of the reacting gases, mixed in their combining ratios, are circulated over it. After the attainment of this steady condition the rate of combination is always directly proportional to the pressure, provided the gases are present in their combining ratios and the products of combustion are rapidly removed from the sphere of action.

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* Bone. ·Report on Gaseous Combustion, British Association, 1910.

Bone has found that metal surfaces, *e.g.*, of silver and gold, while inducing the surface combustion of hydrogen or carbon monoxide, immediately acquire a negative charge. Dealing with this point Sir J. J. Thompson says: "In reference to the influence of hot surfaces in promoting combustion, to which Professor Bone has drawn attention, it is not improbable that the emission of charged particles from the surface is a factor of primary importance. Hot lime gives out an enormous stream of negative electrons travelling with high velocity, whilst hot metals emit an excess of positive electrons, as indeed Prof. Bone had found by the development of a negative charge on the silver foil which he had used as a contact surface.

"These electrons may produce very important effects by uniting (perhaps selectively) with moisture, with the oxygen, and with the inflammable constituents of the gaseous mixture. The mode of action of the oxides is especially worthy of investigation. Chemists recognise two stages of oxidation in baryta and perhaps in lime. It may be that the problem of the source of the energy of the torrent of electrons is to be found in the oxidation and reduction of the contact surface."

He suggested that the action of surfaces might ultimately be found to depend on the fact that they formed a support for layers of electrified gas in which chemical changes proceeded with high velocity.

CHAPTER IV.

RESPIRATION I.

Composition of Air. General Functions of Oxygen and Carbon Dioxide.

Fresh country air contains, by volume, nearly 21 per cent. oxygen and 79 per cent. of inert gas, most of which is nitrogen, mixed with a trace of carbon dioxide (·03-·04 per cent.) and some moisture, the amount of which varies greatly. There are, moreover, in country air and more especially in sea air very few bacteria and very little dust; in mid-ocean the atmosphere is practically sterile. This freedom from noxious substances together with the presence at times of traces of ozone and hydrogen peroxide accounts for the marked beneficial effects of this fresh air compared with the air of towns.

It is generally believed that air in which a candle will not burn is unfit to breathe, and many mining people imagine they have had a narrow escape after passing along a mile or so of roadway in air which would not support the combustion of an oil lamp. The margin of safety is, however, far greater than they suppose, a fact well known to physiologists and some mining chemists.

Air which has been breathed contains, after removal of the moisture, 3½-4 per cent. of carbon dioxide, 17-16½ per cent. of oxygen and 79½ per cent. of nitrogen. As so little of the total oxygen is used it may well be asked, "Is it necessary to have so much oxygen for respiration?" The answer to this is "No! It is not at all necessary." For purposes of respiration an atmosphere containing anything between 14-21 per cent. of oxygen is just as good as ordinary air;

by respiration alone it is quite impossible to detect any difference between ordinary air and air that contains only 17½ per cent. of oxygen. All that is necessary is that the amount of oxygen should not fall below the minimum required to form, with ease, the normal amount of oxyhæmoglobin from the venous blood. Any oxygen in excess of this acts almost as an indifferent gas.

The reason why the air is expelled from the lungs while it still contains 16½-17 per cent. of oxygen is as follows. The depth and frequency of breathing are unconsciously so regulated as to keep the percentage of carbon dioxide in the air in contact with the lungs constant at about 5½ per cent., so that the arterial blood leaving the lungs is saturated with air containing about this percentage of carbon dioxide. It has been found that the slightest increase of carbon dioxide in the arterial blood is sufficient to excite to greater activity the nervous centre which controls and regulates the breathing.

When more oxygen is being used up in the lungs, as is the case while walking and still more so while running or doing hard physical work, this extra oxygen is not taken from the same air by reducing the percentage to, say, 12 per cent. (instead of the usual 16½-17 per cent.), for this would mean that the air in contact with the lungs would contain 12½ per cent. carbon dioxide. The increased quantity of oxygen is obtained by *breathing two or three times the usual quantity of air.* During work the alveolar carbon dioxide pressure rises slightly and the pulmonary ventilation, *i.e.*, the amount of air taken into the lungs, is consequently increased.

Under steady atmospheric pressure, the alveolar air contains a nearly constant percentage of carbon dioxide in any particular person, though the amount varies in different individuals. But if the atmospheric pressure changes, the percentage of carbon dioxide also changes, varying inversely with the total air pressure; consequently the pressure of the carbon dioxide in the lungs remains constant.

The oxygen pressure, however, varies widely under these conditions. As already pointed out, the respiratory nervous centre is very sensitive to any rise in the alveolar carbon dioxide pressure, an increase of ·2 per cent. being sufficient to double the amount of alveolar ventilation during rest. Changes in the oxygen pressure, within wide limits, have no such effects. It is only when the oxygen pressure in the inhaled air falls below 13 per cent. of an atmosphere that the respiratory centre begins to be excited for want of oxygen and the alveolar carbon dioxide pressure begins to fall. *The normal chemical stimulus to respiration is the presence of carbon dioxide and not a diminution in the amount of oxygen.*

A curious phenomenon occasionally noticed is the cessation of breathing which temporarily follows excessive ventilation of the lungs, as happens when one deliberately takes a number of breaths in rapid succession; technically termed *apnoea*, it is sometimes described as "forgetting to breathe." This phenomenon is caused by a fall of carbon dioxide pressure below the exciting point, the oxygen pressure at the same time being sufficiently high not to stimulate the respiratory nervous centre.

The actual quantity of oxygen consumed by a human being varies enormously with the degree of bodily activity and also, though to a smaller extent, with the individual concerned. An average man at rest uses 0·3 litres of oxygen per minute. When walking at 3 miles an hour this is increased to a little over one litre per minute while severe exertion, such as climbing or running, increases it to two litres per minute.

Air containing 75 per cent. or more oxygen behaves as a poison, and pure oxygen acts rapidly, especially when under pressure, producing inflammation of the lungs, convulsions and death.

THE EFFECT OF A REDUCED PERCENTAGE OR TENSION OF OXYGEN.

The oxygen in air at sea level may be reduced to 14 per cent. before any shortage is noticed, and even at this point the effect is very slight and is only observed when hard physical work is being performed. A climber does not notice any lack of oxygen at altitudes below about 9,000 feet, at which height the oxygen tension is reduced to 14 per cent. of an atmosphere. When the amount of oxygen is reduced to 12 per cent. at sea level, or in ordinary air at an altitude of 14,000 feet, the shortage is distinctly noticeable even with the exertion of moderate walking on the level.

A person not exerting himself will fail to observe anything unusual until the oxygen has been reduced to 10 per cent.; at this point the breathing becomes deeper and more frequent and the face somewhat dusky. At 7 per cent. there is distinct panting, accompanied by palpitations, and the face assumes a leaden colour; the mind becomes confused and the senses dulled, although the person affected may be quite unaware of this fact. At a little below 7 per cent. there is a complete loss of consciousness.*

To summarise, air is getting *dangerous* when the oxygen percentage falls to 10, and when it is below 7 per cent. a man cannot exist for more than a short time; his life is extinguished at 7 per cent. as a candle flame is at 17 per cent. of oxygen.

While considering the effects of a reduced amount of oxygen, it is of interest to note that human beings are found, in different parts of the world, living at altitudes as high as 14,700 feet where the partial pressure of oxygen is only 12 per cent. of an atmosphere.

The Indians dwelling on the upper slopes of the Andes are a hardy and vigorous race, square shouldered and with broad, capacious and very long chests. The inhabitants of the high plateaus of Tibet combine physical vigour with great activity.

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* *Journal Physiol*, 1905, xxxii., 225 and 486.

Dr. Leonard Hill writes: "It is well known that men can work hard and live vigorous healthy lives in the mountainous regions of the earth, where the partial pressure of oxygen is only 17 per cent. of an atmosphere or less. In the Alps there are noted health resorts at very high altitudes, and the Alpine guides and soldiers are the healthiest of men. Mexico City and Johannesburg were built at an altitude of about 6,000 feet.

"In the Andes railways have been built and mines worked at altitudes of 12,000 to 15,000 feet, and several towns with large populations exist at 10,000 feet. The human organism easily compensates itself for the diminution in the partial pressure of oxygen. The ventilation of the lungs and the percentage and total amount of hæmoglobin increase, while the power of the hæmoglobin to hold oxygen in combination also changes, with the result that the tissues obtain an adequate amount of oxygen."

Paul Bert believed that under normal pressure we consume much more oxygen than we need, just as we customarily eat more food than is necessary. The Swiss mountaineer sustains his strength with a piece of bread and a few onions while the member of the Alpine club, on the same ascent, requires a pound of meat. Probably the native mountaineer is able to cut down his consumption of oxygen without suffering any loss either of body temperature or of power to perform work.

Valenzuela arrived at similar opinions by studying the relation between altitude and percentage of deaths from tuberculosis in Spain: above 4,000 feet tuberculosis is entirely unknown and the percentage of deaths from it at altitudes above 1,500 feet is less than half of the percentage below that level. From his long experience he came to the conclusion that the beneficial effects of high altitudes, in cases of consumption, are due to the diminution of oxygen tension and not to the mechanical influence of reduced total pressure.

He proved this by an ingenious method of causing his patients to breathe, at sea level, an artificial atmosphere that contained only 17 per cent. of oxygen, this amount corresponding to an altitude of 5,500 feet. He found that this stimulated the respiratory movements, increased the chest expansion and augmented excretion of carbon dioxide and urea, while nutrition was in no way diminished.

Other investigators who have experimented with reduced oxygen atmospheres have arrived at the same conclusion regarding the beneficial action of a reduced percentage of oxygen: they find that it produces quiet sleep, increases the appetite, diminishes coughing and fever and causes a gain in the lung capacity and the weight of the body.

Before leaving this matter the effect of changes in atmospheric pressure at sea level should be considered. Even with the ordinary changes in the barometer the tension of oxygen varies greatly, the variation between the extremes being some 10 per cent. of the total value. From the standpoint of respiration this is just as if the oxygen was reduced by 3 per cent. to, say, 18 per cent. while the pressure was maintained constant at 31 inches of mercury. For the purposes of respiration such air would be equivalent to ordinary air containing 21 per cent. of oxygen when the barometer was at 28 inches.

In the case of combustion it is the *percentage* amount of oxygen that matters, but in respiration it is (within limits) the actual quantity, *i.e.*, the weight in a given volume, that counts. A cubic foot of air with an oxygen percentage of 17½ contains, at sea level, almost exactly the same weight of oxygen as an equal volume of air with 21 per cent. of oxygen at an altitude of 5,000 feet. A lamp will not burn in the former but will, of course, burn quite readily in the latter: for respiration they are exactly alike.

The Influence of Carbon Dioxide.

The effect of atmospheric carbon dioxide on respiration has been the subject of much research by physiologists. The quantity normally present in fresh country air is about 4 parts per 10,000, *i.e.*, 0·04 per cent. by volume. In towns, and rooms it is a little more, but, except in theatres and crowded rooms, it seldom exceeds 0·1-0·2 per cent.

In the air of mines it is very variable, but even here it is not often more than 0·5 per cent., and on the average is very much less than this, generally less than 0·1 per cent. It has been shown by many investigators that, when unaccompanied by organic matter, a moderate amount is not at all harmful; 1-1½ per cent. of carbon dioxide is in no way injurious; it increases the depth or frequency of breathing by one-sixth, which is not noticeable, and it certainly has no bad effect in ordinary air or in air containing 17½ per cent. of oxygen. Three per cent. of carbon dioxide in air doubles the frequency or the depth of breathing; it is distinctly noticeable, and possibly air containing this amount, if breathed regularly and continuously, would be harmful.

The function of carbon dioxide in regulating the breathing has already been pointed out. Haldane found that the percentage of carbon dioxide in the air cells of the lungs, in a mine 2,600 feet deep, was distinctly lower than at sea level, and very much lower than at the top of Ben Nevis (4,400 feet). The pressure of carbon dioxide per square inch was, however, the same in each place. It follows that the percentage, and still more the pressure, of the oxygen in the air cells of the lungs is greater down a mine than on the surface, unless the oxygen percentage is greatly diminished without a corresponding gain in the amount of carbon dioxide, or so greatly diminished that increased breathing cannot compensate in any way for the deficiency.

Such slight increase in the amount of carbon dioxide (up to, say, 1 per cent.) and deficiencies in oxygen as ordinarily occur in air, where a light will still burn, are evidently therefore of no physiological importance, although their effects have often been supposed to be very serious.*

The amount of carbon dioxide in air must be as much as 6-8 per cent. in order to produce toxic symptoms and about 25 per cent. is necessary to cause actual danger to life, but even this amount can be breathed for several hours.

Professor Benjamin Moore, F.R.S., of Liverpool University, has kept animals in an atmosphere containing 14 per cent. of carbon dioxide for 48 hours and found that they experienced no ill effects. Prof. Haldane* gives the following description of the influence of carbon dioxide. "At about 5-6 per cent. there is marked panting, accompanied by rise of pulse. At 10 per cent. there is violent panting, throbbing and flushing of the face; headache is also produced, especially on a return to fresh air. Above 10 per cent. it begins to have a narcotic effect and at about 25 per cent. death may occur after several hours, but as much as 50 per cent. can be breathed for some time without fatal effects."

Dr. Leonard Hill has made observations on the men who filled the carbonic acid cylinders in the Albion Brewery, London. They worked in a room where there was usually an excess of carbon dioxide and had worked in it long shifts each day for many years. He found that the gas had no injurious effects on the men, who were all quite healthy. The same investigator has also experimented on animals and he writes: "I have animals now doing well and putting on weight, although living continuously in 2-3 per cent. of carbon dioxide in air which has been breathed by other animals."

In Dr. Whalley's report on the ventilation of mines in Scotland, he describes one place where a lot of black-damp was evolved, "A light would not burn 1½ feet from the floor or in the waste, but the men had no fault to find with the atmosphere, and the foreman told me it was better than usual." Three samples of the air gave on analysis the following results:—

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* Foster and Haldane, "Investigation of Mine Air," p. 144.

	CO_2.	O_2	N_2.
(1) On pavement	4·56	13·13	82·28
(2) At roof	0·69	20·08	79·2
(3) At coal face	1·21	18·97	79·8

It is very generally believed that carbon dioxide produced in respiration has a bad effect if breathed again. If this is true it cannot be attributed to the carbon dioxide itself, but must be due to some other constituent. By some it is supposed that this effect is caused by poisonous organic compounds in the exhaled gas. But against this, Dr. Leonard Hill says:* "It has been often asserted that there was some organic chemical poison exhaled in the breath. I have carefully sifted the evidence on which this assertion was based and find that there is none worthy of credence."

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* *J.I.M.E.*, vol. xliii., part 3, p. 285.

CHAPTER V.

RESPIRATION II.

The Influence of Water Vapour and Temperature.

The influence of the water vapour in air is far greater than was formerly supposed. It is the water vapour present in crowded rooms that causes the discomfort and stuffiness.

In hot mines the proportion of water vapour present is of particular importance. At a wet bulb temperature of 70° F. a mine or a room begins to be uncomfortable and stuffy. At 80° F. wet bulb the amount of continuous work a man can perform, without increase of bodily temperature, rapidly diminishes and is reduced to practically *nil* at 90° F. even though, as in hot mines, very little clothing is worn.

Even to remain at rest for any length of time is difficult when the wet bulb is at or above 90° F. Professor Haldane says*: "In an atmosphere at 93° F. wet bulb, stripped to the waist and doing practically no work, I found it impossible to stay. The temperature of the body rose 5° in two hours and finally I had to come out."

It is, of course, common knowledge that, if the air is dry, much higher temperatures than 90°-93° F. can be borne with ease and comfort. In a mine with dry moving air at 90° F. men can work quite well, and even 100° F. is not uncomfortable. In hot climates men often work hard at temperatures considerably above 90° F. but the air is not saturated with moisture. Miners working a drill driven by compressed air in a hot mine are not affected by temperatures even higher than 90° F., the air from the drill carrying only a small amount of water vapour.

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* Haldane, Report on the Health of Cornish Miners, 1904, p. 24.

It appears to be just as necessary for the body to get rid of a large quantity of water during respiration as it is for it to get rid of the carbon dioxide. At about 90° F. air saturated with moisture holds about 5 per cent. of water vapour by volume; such air does not allow the body to vapourise water quickly enough and is consequently unfit for breathing.

Dr. Leonard Hill made direct experiments to test this point. In his laboratory he had a closed chamber containing 3 cubic metres of air. In this he confined, on several occasions, eight students until the oxygen fell to about 16 per cent. and the carbon dioxide increased to over 4 per cent. At the same time the temperature of the enclosed air rose to 84° F. wet bulb. The discomfort felt by the students was relieved by switching on an electric fan within. This made it evident that the discomfort was caused, not by lack of oxygen or excess of carbon dioxide but by the stagnation of bodily heat. The air confined in the clothes and between the bodies of the students was nearly motionless, while at the same time it was warmed almost to body temperature and saturated with moisture. The skin (the cooler of the body) could not act properly; the blood congested in the skin, sweat bedewed the face and body, and the heart wearied of its rapid beat.

On whirling the air in the chamber, which was at 85° F., a cooling effect was produced and this gave relief. Relief was not obtained by one within who breathed, through a tube, the pure air outside the chamber, nor was discomfort caused to one who, outside the chamber, breathed, through a hole, the impure air within.

All the evidence goes to show that men endure, not only with impunity but with splendid health, confinement in an ill-ventilated close atmosphere for some hours, provided they are exposed to a cold and bracing outside air for much of the day. North sea fishermen, shut up in their cabins, sometimes sleep in air which may have become so impure that a lamp goes out in it.

From these important observations by Dr. Leonard Hill it appears that the full effect of a hot damp atmosphere is only felt when it acts on both the skin and the lungs. This is an important fact to remember when considering certain conditions under which men are sometimes called upon to work, using oxygen respirators.

The above results are fully borne out by Prof. Cadman's observations* on the effect of temperature on miners. He found that the influence of heat depended entirely upon the temperature recorded by the *wet bulb* thermometer no matter what the dry bulb might register.

At 72° F. wet bulb it was observed that heavy clothing was discarded and light clothing only used. At 80° F. wet bulb, provided the maximum body surface was exposed, hard work was possible, the capacity for work being greatly increased if a breeze or current of air passed over the body. From 80-85° F. wet bulb, work was seriously affected and hard work was impossible.

In some cases it was noticed that one effect of watering the roadways, to prevent dust explosions, had been to increase the wet bulb temperature to such an extent that the labour capacity of the miners was lessened. This effect was also noticed in places where natural excretions of water from faults and joints had caused a rise in the wet bulb reading. No such inconvenience was experienced by those employed in other parts of the same mine where the wet bulb temperature had not altered, the dry bulb reading being the same in both cases.

From these investigations it is evident that the amount of water vapour in air, especially in warm mines, is of great importance. The author has designed for mine work a very convenient set of wet and dry bulb thermometers which can be carried in the pocket. The thermometers are protected from injury by metal, each being enclosed in a case which has just enough of the metal cut away to allow air to circulate freely round the bulbs and to permit of the scale being read.

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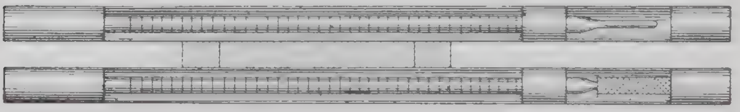
* Blue Book, Cd. 4551.

With the usual stationary hygrometer it is necessary to have the bulbs 6 to 8 inches apart, but with this pocket form it is found that, when the thermometers are waved about rapidly, the fact that the bulbs are close to one another does not introduce any appreciable error.

In the earlier sets some inconvenience was experienced by the thread of the mercury breaking, but this has been overcome by having the space above the mercury filled with nitrogen. The wet bulb can be moistened by water carried in a small tube without taking the thermometer out of its case. In mining work care must be taken that the dry bulb is quite dry; often moisture will settle from warm moist air on a cold dry bulb, and if this happens it must be wiped away. The hygrometer described is provided with means for wiping the dry bulb without removing it from its case.



Pocket Hygrometer.
J. W. Towers, Ltd., Widnes.

Many places occur in warm mines where it is difficult or undesirable to use the ordinary ventilating current of fresh air, and in such places the air soon becomes very hot and saturated with water vapour. In the neighbourhood of a gob fire the temperature is often above 100° F., and sometimes very much higher. It is, of course, impossible for men to work long in air testing over 90° F. wet bulb without serious injury to health. Short spells of work in such places, however, do not appear to have any very bad effect, provided that poisonous gases are absent.

At such times, especially when there is the possibility of carbon monoxide being present, it might be found advantageous to use a small light respirator that would dry the air and remove all traces of carbon monoxide. For this purpose, the author has devised a respirator in which carbon monoxide is removed by a preparation made from animal blood, while moisture is removed by calcium chloride or caustic soda contained in a light sheet-iron vessel that is strapped on the back.

INFLUENCE OF CARBON MONOXIDE (CARBONIC OXIDE).

This gas often occurs in mines, in fact recent work* has shown that, even in well-ventilated mines, carbon monoxide is a constant constituent, ·002-·004 per cent. being found in the main air-returns. It is obvious that if the places where the carbon monoxide is formed are not easily ventilated, the percentage of this gas is likely to be much greater there.

Carbon monoxide readily unites with the hæmoglobin of the blood to form a stable compound and it is for this reason that it is extremely poisonous. Its affinity for hæmoglobin is three hundred times greater than that of oxygen, and it has been estimated that if air containing 0·08 per cent. carbon monoxide is breathed for two or three hours, one half of the blood will be converted into carboxyhæmoglobin.

As little as 0·17 per cent. of carbon monoxide is sometimes fatal to animals, but about 0·4 per cent. is required to cause death within a moderate time. Any percentage above 0·15 must be regarded as distinctly dangerous and anything above 0·03 per cent. will produce unpleasant symptoms.

The sources of carbon monoxide in mines are:—

(i) Explosives that are unsuitable or are carelessly used.
(ii) Gob fires.
(iii) Explosions of fire-damp and dust.
(iv) Fires on the roads.
(v) The oxidation of some varieties of coal and dust.

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* Mallard and Deact, *Comptes. Rendus*, *1910*, 151, 645 and 647.

Gob fires are perhaps the most general cause of dangerous quantities of this gas, and it is produced even when coal heats up slightly in the waste, although such heating may never develop into a gob-fire. In the course of some recent work by Mahler, powdered coal (from Courrières) after being freed from moisture and occluded gas, was found to absorb oxygen from air, which combined with the coal forming water, carbon dioxide and carbon monoxide. From 150 grams of coal there were obtained:—

1 c.c. of CO_2 and 2·88 c.c. of CO. in 30 hours at 25–30° C.
12 c.c. of CO_2 and 4·97 c.c. of CO. in 30 hours at 85° C.
30 c.c. of CO_2 and 6·67 c.c. of CO. in 30 hours at 105° C.

These results indicate that traces of carbon monoxide are likely to be present in all mines, and that appreciable amounts of it may be found in hot mines, in the neighbourhood of gob fires and in badly ventilated parts. Indeed, it is very probable that the fire-damp and black-damp found in mines always contain traces of carbon monoxide; this is a matter which requires further careful investigation.

The symptoms of carbon-monoxide poisoning are headache, inability to walk, and finally unconsciousness. These symptoms are very similar to those caused by alcoholic poisoning, and are due to oxygen hunger, so much of the hæmoglobin having been used up that there is not sufficient left to supply the body with the necessary amount of oxygen.

The treatment for carbon-monoxide poisoning in slight cases is fresh air, the patient either walking or, what seems to be rather better, taking a long motor ride. In more serious cases oxygen must be administered.* It has been found that oxygen containing 4 per cent. of carbon dioxide is much more effective than pure oxygen, as the patient is, by this mixture, compelled to breathe more quickly and so gets rid of the carbon monoxide sooner. At mines that are subject to gob fires a supply of special oxygen containing about 4 per cent. of carbon dioxide should always be at hand.

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* The poisonous nature of pure oxygen must not be overlooked, and the gas must not be used longer than necessary.

Statistics show that work in British collieries is extremely healthy—much more so than many occupations above ground. But it sometimes happens that miners suffer in health for no obvious reason. This is usually attributed, quite erroneously, to the action of carbon dioxide, or to lack of oxygen. It is far more likely to be due to traces of carbon monoxide or some other poisonous gas, present in such small quantity that an ordinary gas analysis does not reveal it.

With the exception of palladium chloride there are no chemical reagents by which carbon monoxide in the mine air can be detected on the spot and even the palladium method requires considerable practice and care to give accurate results.

A small animal or a bird, such as a canary, is affected much sooner than a man and this well known test is, at the present time, the only one which is available for the miner. A small bird or mouse is affected in approximately one-tenth the time required to affect a man, so that this test is perhaps unduly sensitive.

THE INFLUENCE OF SULPHURETTED HYDROGEN.

This gas may be present in mines owing to the heating of coal or to blasting with powder. Small traces of it are probably contained in most fire-damps. It may be formed by the action of acid on sulphides and it is also generated by certain bacteria. Water that contains sulphuretted hydrogen in solution will sometimes, on agitation, give off dangerous quantities of gas.

Lehmann has shown that ·05 per cent. of sulphuretted hydrogen produces alarming symptoms, while ·07 per cent. will cause death (of men as well as animals) in about an hour; 0·2 per cent. is sufficient to kill dogs and cats in about a minute and a half. Sulphuretted hydrogen is reckoned to be five times as poisonous as carbon monoxide.

The symptoms of poisoning by this gas are first of all irritation of the eyes and air passages. With a slightly increased quantity of the gas, some bronchitis is set up together with inflammation of the eyes, accompanied by great pain; the pain in the eyes is especially *felt afterwards, often during the next night.* ·05 per cent. of sulphuretted hydrogen produces giddiness, vomiting, catching of the breath and other signs of irritation. In cases of poisoning by sulphuretted hydrogen men are generally rendered unconscious very suddenly, and man after man is overcome in the same way in attempting to rescue. Even if rescued, the men often die after a temporary recovery (as is the case, too, with carbon-monoxide poisoning). When sulphuretted hydrogen is present in considerable quantity it cannot be detected by the smell: it is only when very dilute and comparatively innocuous that the characteristic smell of rotten eggs is evident. At underground fires the smell is masked by the other odours. But this gas can easily be detected by the blackening it causes on a strip of paper dipped in lead acetate solution. Air in which the paper is blackened within a minute is dangerous to breathe. When it is necessary to work in an atmosphere that contains sulphuretted hydrogen, the best safeguard is a Towers respirator. This is made of vulcanite and a fresh charge of absorbent is placed in it before use. The absorbent consists of fine uniform pieces of charcoal laden with caustic soda.

Influence of Nitrous Fumes.

This gas may occur in a mine as a result of blasting or shot firing; nitro-glycerine and nitro-cellulose give both nitrous fumes and carbon monoxide.

Nitrous fumes have an irritant action on the eyes and air passages; they are very dangerous and even in small quantities have caused many deaths. The *immediate* effect of breathing them is often slight but after a few hours acute bronchitis develops and is often fatal within 48 hours.

Dr. J. S. Haldane has recorded the fact that mice exposed to air containing 0·05 per cent. of nitrous fumes were only slightly inconvenienced at the time but died within 24 hours. In fact nitrous fumes are even more dangerous than sulphuretted hydrogen.

They are easily recognised by the smell, and any place in which, after shot firing, the smell of fuming nitric acid can be detected, is not safe and should be avoided until cleared. Paper that has been steeped in starch and potassium iodide solution is turned blue even by traces of nitrous fumes.

CHAPTER VI.

THE MECHANISM OF EXPLOSIONS.

The phenomena of explosions in general offer so wide a field that a full treatment cannot be attempted here, but a brief survey of our present knowledge is necessary before passing on to consider the phenomena of dust and gas explosions in mines.

There are many substances and mixtures of substances which can be artificially prepared and which are so unstable that on the application of a little energy, such as heat, sunlight, or a moving hammer, they react with great violence, more stable products being formed. The influence of this small amount of external energy has been compared to the action of a trigger, in that it is almost instantaneously followed by the liberation of a vastly greater amount of energy. Reactions of this kind, which exhibit great violence, are called *explosions.*

Examples of the liberation of energy in this manner are afforded by the behaviour of nitrogen iodide, which explodes when touched with a feather, by that of a mixture of hydrogen and chlorine, which explodes after a few seconds' exposure to bright sunlight, and by that of dynamite, which can be detonated by a blow from a hammer or by other suitable shock; the explosion of a small quantity of mercury fulminate can cause the violent detonation of a large mass of dynamite, and mercury fulminate can itself be detonated by friction.

These reactions are of a different nature from quick combustions since they are practically instantaneous; every particle appears to change at the same instant. On ignition, gunpowder and dynamite burn rapidly but without violence, whereas when detonated by a suitable shock enormous violence is developed.

A similar distinction between explosion and rapid combustion can be drawn in the case of mixtures of oxygen with inflammable gas; with some mixtures, fired under certain conditions, the change is practically instantaneous and is always attended with great violence; with other mixtures, the change is merely a quick combustion, which proceeds rapidly through the mass and, on the large scale, exhibits considerable violence. In the case of mixtures of air* with marsh gas or with coal-dust the change is usually of the latter variety, *i.e.*, a rapid combustion. It may be that a true detonation of such mixtures is possible, but this has not hitherto been proved.

Between 1815 and 1825 Sir H. Davy carried out much research work in order to determine the causes of explosions in coal mines, and he ascertained many important facts in connection with the ignition of explosive mixtures, *e.g.*, the influence of cold solid surfaces in retarding the propagation of combustion. He also determined the explosive limits of some combustible gases with air.

Our knowledge of the phenomena of gaseous explosions was extended by Bunsen, who effected great improvements in the methods of gas analysis. It was due primarily to Bunsen's work, or rather to his interpretation of the results, that many errors in regard to gaseous combustion crept into chemical literature; some of these errors persist even in text books of quite recent date.

From his measurements of the pressures developed during the explosions of carbon monoxide and of hydrogen with half their volume of oxygen, Bunsen concluded that only one-third of the gas mixture combined during the first phase, the combination of the remaining two-thirds occurring during the later stage of cooling. This view was generally accepted until quite recent times, though it is now known to be erroneous. Moreover, his explanation of the results obtained in measuring the minimum rate at which an explosive gaseous mixture must be sent through a tube in order to prevent the flame "striking back" led to mistaken views regarding the speed of propagation of flame in gaseous explosions. What Bunsen actually measured here was merely the initial speed during ignition of the gas.

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* Mixtures of methane with oxygen and nitrogen in the proportion indicated by $CH_4 + 4N_2 + 2O_2$, or with more oxygen, will develop a true explosive wave.

The erroneous views which attributed selective combustion to the hydrogen in hydrocarbon flames originated from the faulty interpretation given to some of the results of Davy and Bunsen. Even at the present day this notion of the preferential combustion of hydrogen is prevalent among chemists, and is still stated, as an article of faith, in some text books.

Accurate measurements of the speed of gaseous combustion were first made by MM. Mallard and Le Chatelier, and by MM. Berthelot and Vieille, who independently discovered, in 1881, that the initial velocity of combustion is rapidly accelerated until it attains the final enormous velocity of the explosive wave or *detonation*, and that this final velocity is *constant*.

The burning of a mixture of inflammable gases can be effected in two ways:—

(1) By the combustion of one layer igniting the layer adjacent to it (ordinary rapid combustion).

(2) By the transmission of a sufficiently high pressure suddenly applied. This raises the whole mass to its ignition temperature, and the consequent combustion causes a further rise of temperature and corresponding increase of pressure, the change being practically instantaneous throughout the mass. Combustion in this manner is called *detonation*; it is characterised by its enormous velocity, intense luminosity and the high pressure instantaneously set up.*

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* Velocities, however, exist that are intermediate between these two.

When an explosive mixture is fired by a spark or flame in a long tube, the flame is usually propagated along this tube with an increasing velocity until at a certain distance from the ignition point (depending upon the nature of the gases) it reaches its maximum and the explosion wave is set up, and is propagated almost instantly through the whole mixture. The firing of a fulminate in such a mixture sets up the explosion wave *at once*.

The following values were obtained by Berthelot for the velocity of the flame of combustion in mixtures of hydrogen and oxygen at varying distances from the point of ignition:—

Distance of flame from point of ignition.	Duration observed.	Mean Velocity per Second.	
		From the start.	During each interval.
0·020 metres*	0·000275 secs.	72·72 m.	72·7 metres
0·050 ,,	0·000342 ,,	146·20 ,,	448·0 ,,
0·500 ,,	0·000541 ,,	924·4 ,,	2,261·0 ,,
5·250 ,,	0·002108 ,,	2,491·0 ,,	3,031·0 ,,
20·190 ,,	0·007620 ,,	2,649·0 ,,	2,710·0 ,,
40·430 ,,	0·015100 ,,	2,679·0 ,,	2,706·0 ,,

These figures show that the velocity increases rapidly from the starting point up to the fiftieth centimetre; after this distance the values obtained may be regarded as almost constant, within the limits of experimental error. Berthelot stated that the establishment of a regular explosion wave can only be effected successfully when the sparks used to inflame the mixture are sufficiently strong. If feeble sparks are employed, the period of varying velocity can be greatly prolonged.

In some combustible mixtures, *e.g.*, those of air with methane or coal gas, a true explosion wave cannot be set up under ordinary conditions. In these cases the flame is propagated irregularly or with vibratory movements, and it sometimes becomes extinguished; the pressure is variable, whereas during a true explosion wave the pressure is constant.

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* 1 metre = 3·28 feet.

The propagation of the explosive wave is quite a distinct phenomenon from that of ordinary combustion. It occurs only when the layer of ignited gas exerts its maximum possible pressure upon the next layer, *i.e.*, when the ignited molecules possess their maximum velocity, so that they preserve almost the whole of the heat developed during the chemical reaction. What is propagated is not the gaseous mass but an undulatory movement: the wave is the same in a tube open at both ends, open at one end, or closed at both ends.

Professor H. B. Dixon defines the explosive wave as being that flame which passes through a uniform gaseous mixture with a permanent maximum velocity. He says that this velocity is a definite physical constant for each mixture, and that it is approximately equal to the velocity of sound in the burning gas. "Since the gas at the point of combustion is itself moving rapidly forward in the same direction as the wave, the actual velocity is, in consequence, much greater than that of sound in the gas mixture at ordinary temperatures."

The Influence of the Source of Ignition.

The conditions under which explosive gas mixtures can be ignited, by electric sparks, blown fuses and incandescent metallic and carbon filaments, are of importance to practical mining people, because of the increased application of electricity to underground haulage and signalling and to the increased use of electric lamps.

Wüllner and Lehmann investigated the action of hot wires and found that the gas mixtures appeared to be ignited by iron and copper wires at the moment of fusion, when ionisation* is in active progress.

In 1898 Heise and Thiem investigated the effect of breaking small incandescent lamps, while running at 65-220 volts, in explosive mixtures of marsh gas and air. They found thick filaments were more dangerous than thin ones, that electric switches opened in the explosive mixtures began to give ignitions with 1·75 ampères at 100 volts direct current, that fuses on melting always gave ignitions and that white hot carbons did not; also that continuous current motors did when starting. They concluded that all visible electric sparks were to be looked upon as dangerous.

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* Ultra-microscopic particles (called electrons) carrying an electrical charge are shot out of the metal.

In 1911 Prof. Lemaire found that metallic filament lamps of even very low voltage will cause ignition if broken in explosive gas mixtures. Mr. H. H. Clark, of the Bureau of Mines, U.S.A., has confirmed this by breaking small electric filament lamps in explosive mixtures.

Quite recently, in October, 1912, Prof. Thornton* contributed to The Institution of Mining Engineers a most complete investigation of the ignitability of explosive gas mixtures by single electric flashes made by breaking a contact in the gas mixture. Direct and alternating currents of different voltage and power and varying frequency were tried and also the effect of using different kinds of metallic poles. In this investigation it was clearly established that alternating currents, especially high frequency currents, are much safer than direct current for signalling and haulage in mines. Prof. Thornton's paper should be carefully studied by all who have to do with the electricity supply in mines.

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* "The Ignition of Coal-gas and Methane by Momentary Electric Arcs," *Trans. Inst M. E.*, vol. xliv., part 1.

CHAPTER VII.

THE RÔLE OF COAL-DUST IN EXPLOSIONS.

PART I.—HISTORICAL.

Government returns show that the occupation of the miner is healthy but dangerous. The chief risks run by miners are four: (1) falls of the roof and sides, (2) haulage accidents and (3) shaft-accidents. Casualties due to explosions of fire-damp and coal-dust come fourth on the list,* comprising 11 per cent. of the total. Judging from the magnitude of some recent explosions in mines, it appears that if it were not for good luck, together with the admittedly good management, the death roll from this cause would not be so comparatively small.

There are many indications that the mines to-day are more dangerous than they were in the previous generation, the increased risk being due to the ill-considered speeding up of ventilation, which adds enormously to the possibility of *dust* explosions. At the International Congress on Mine Safety and Testing Stations, held in Pittsburg in September, 1912, Mr. G. S. Rice stated that not only were mine explosions more frequent in America than in any other country, but that the number of them during the last ten years had been greater than ever before.

The fact that there are not nowadays so many lives lost per 1,000 miners at work or per 1,000 tons of coal obtained, does not prove that the mines are in themselves safer than they formerly were. The diminished death roll is due to the enormous number of precautions now taken to prevent the *starting* of explosions, *i.e.*, to prevent the first ignition of gas and dust; safety-lamps have been much improved, and are more guarded and inspected; more safety-lamps and fewer naked lights are used; dust is watered before a shot is fired; and last, though by no means least, managers are better educated and are more careful, at the first sight of real danger, to withdraw the majority of the men.

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* The number of *deaths* from explosions comes third on the list, and for an average of ten years ending 1911 was 11 per cent. of the total men killed underground (see appendix).

Yet in spite of all precautions, there are, under present conditions, factors which make ignitions possible, and over which the management has, in many cases, no control whatever. It must not be overlooked that a gigantic explosion, such as that at Courrières with its thousand victims, is possible in many of our large mines. Even while exercising the most careful supervision, many managers are in a constant state of anxiety; they know that the conditions are risky since air and dust must be present together, and they feel that there are indefinable factors at work, of which they have neither knowledge nor control. If no accident happens they admit it is largely the result of "good luck."

It will be shown, in the course of the following pages, that this anxiety can be removed; that our knowledge of the properties of coal-dust is sufficient to enable us to eliminate this element of luck and to bring about, not merely a safer atmosphere, but a condition of absolute safety.

History of our Knowledge Regarding the Influence of Coal-dust in Explosions.

The first record of the influence of coal-dust in mine explosions is contained in a report by John Buddle on the Wallsend explosion 1803. The mine workings were dusty and some of the survivors were burnt by the sparks of ignited coal-dust.

In 1844 Faraday and Lyll drew attention to the effect of dust in extending the explosion at Haswell Colliery in that year; speaking at the Royal Institution, Faraday said: "The ignition and explosion of the fire-damp mixture would raise and kindle the coal-dust which is always pervading the passages, and these effects must in a moment have made the part of the mine, which was the scene of the calamity, glow like a furnace."

M. Verpilleaux in France, in 1867, as a result of his experiments, came to the conclusion that coal-dust was an important factor in mine explosions.

After an explosion which occurred in a mine of the Campagnac Collieries, where fire-damp had never been detected, M. Vital in 1875 carried out some experiments which led him to believe that very fine coal-dust would increase the intensity and range of a fire-damp explosion.

In the course of his inquiries into explosions (begun in 1870), William Galloway made some experiments in 1875, and read a paper* on the subject before the Royal Society in March, 1876. His first expressed opinion in 1875 was that a mixture of air and fire-damp, which would not be inflammable alone, would become so when coal-dust was added. After the Llan Colliery explosion, December, 1875, Galloway made investigations and said, "Coal-dust has undoubtedly played the most important part in the explosion."

In a paper read before the North of England Institute of Mining and Mechanical Engineers in 1876, Sir H. Hall describes some large-scale experiments performed by himself and Mr. Clark in an adit 45 yards long. Coal-dust was laid on the floor and a cannon fired at the face. This ignited the dust and the flame travelled the whole length and developed considerable force.

In 1878 Prof. Marreco,† after carrying out some experiments jointly with Mr. W. Cochrane and Mr. Morrison, concluded that it was unnecessary to have any fire-damp present that a mixture of coal-dust and air alone could be ignited.

Prof. W. Galloway, in 1880, after investigating the causes of various explosions, including those at Risca and

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* *Proc. Roy. Soc.*, 1876, vol. xxiv., page 239.

† *Trans. N. of Eng. Inst. Min. and Mech. Eng.*, 1878-1879, vol. xxviii., page 85.

Seaham, expressed his belief that fire-damp is altogether unnecessary for the propagation of flame, with explosive effects, by a mixture of dry coal-dust and air.

It would appear then, from the literature, that the first to prove that an explosion could be caused by coal-dust and air alone without any fire-damp were Sir H. Hall and Mr. Clark.

After the Seaham explosion, Sir F. Abel experimented in 1880 with the dust from Seaham and also with gas and dust from Garswood Hall Colliery, Wigan. He found that when the mixture of gas and air was heavily laden with dust as little as 2 per cent. of fire-damp would cause the mixture to become inflammable, and he further added the following most important observation: "*Such dust particles need not be inflammable or combustible to produce the results named.*" He discovered that the flame from a blown out shot extended about 20 feet but might be as much as 35 feet in a narrow gallery. With coal-dust in the air the flame stretched to 80 feet or more, and it extended also to some distance in the opposite direction, against the air current.

It is of interest to note that in 1882 MM. Mallard and Le Chatelier, members of the French Fire-damp Commission, in recording their results, said that coal-dust was not a serious danger and that no colliery explosion of any magnitude could be attributed to coal-dust.

In 1880, experiments in a chamber 82 feet long by 18 inches deep and 16 inches wide were carried out by the Chesterfield and Derbyshire Institution of Engineers. Out of 134 tests with various mixtures of coal-dust and air, 36 ignitions were obtained, while out of 46 experiments in which fire-damp was present, in addition to dust and air, the number of ignitions was 21. In no instance was there any violence or anything in the nature of a forceful explosion even with 6 per cent. of gas present. In the dust and air experiments the clouds of dust were so dense that a man would have been suffocated in them; it was *assumed* that if these would not ignite, less dense ones certainly would not. No single ignition was obtained with less than 90 grains of powder in the pistol used for producing ignition. A candle flame or gas flame never once gave ignition, and in no case did ignition occur even with the pistol unless the dust was in suspension.

In 1884 and onward a most important series of experiments was carried out at Saarbrücken, by the Austrian Fire-damp Commission, in a chamber 167 feet long, with elliptical cross section of 17½ square feet, with which a side gallery 33 feet long was connected (see page 65).

Sir Henry Hall* in 1890 made some large scale experiments in various shafts. In one of the experiments of the third series a most violent explosion resulted, of which he says: "The dust was ignited, followed by a continuous roar and a rush of flame completely filling the pit mouth and ascending 60 feet in the air . . . . : the violence carried some of the woodwork 37 feet above the pit mouth." This was one of the experiments carried out in the Big Lady pit, 210 yards deep and 8 feet in diameter. The air in the pit was tested and found to be free from fire-damp. Sir H. Hall summed up with the words: "These experiments conclusively prove that blasting in dry and dusty mines may cause serious disasters in the entire absence of fire-damp. It is impossible to explain why many of the experiments failed to cause explosions or to ignite the dust, but the fact that at intervals these did occur perfectly justifies the above conclusion."

Thus, up to 1891, the large scale experiments of Galloway, Abel, The Chesterfield Institute, and the more important ones of Hall and the Austrian Commission, were inconclusive. In some cases ignitions were obtained with a blown-out shot (or an imitation of one); in other instances no ignition resulted.

In the final report of the Austrian Commission, 1891, it was stated that their experiments confirmed the previous results, but showed that the dangers were much greater than had hitherto been admitted. They concluded that black powder and similar explosives were dangerous, and that their use should be prohibited in fiery mines. In this investigation their experiments were confined to high explosives (dynamite No. 1), the cartridge lying loose or being covered with only a slight layer of coal-dust. 353 experiments were performed and these showed that many notoriously dangerous dusts were less inflammable than other dusts which were supposed to be much less dangerous. All the tests were made with a charge of 100 grams* of explosive and in nearly every case an ignition was obtained with this quantity. Their main conclusions with regard to dust were as follows:—

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* Blue Book, C. 7401—1.

(1) The degree of inflammability can scarcely be deduced from the chemical composition.
(2) The texture of the coal is important.
(3) As a rule the sensitiveness increases with the dryness.
(4) The chance of a dust explosion appears to depend more on physical conditions than on the chemical composition.
(5) A blown-out shot with coal-dust tamping, or a charge of dynamite lying free, will ignite every kind of coal-dust. Most were ignited by 100 grams and all, without exception, by a charge of 300 grams (about 11 ounces).
(6) A coal-dust which otherwise is not dangerous and takes fire only with difficulty may give rise to a disastrous explosion if there is a little fire-damp present.

In a previous report this same Commission had, as the result of experiments, classified the various coal-dusts as being (*a*) explosive, (*b*) slightly explosive, (*c*) inflammable, (*d*) safe. One of the dusts they described as safe came from Camphausen Colliery, and shortly after the report appeared a violent explosion occurred at this colliery, although no fire-damp was present; it was one of the worst explosions on record, over 200 lives being lost in it.

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* 1 oz. = 28·35 grams.

In addition to the experimental results which have been summarised above, it is important to consider the evidence of miners and of others who were engaged in actual mining practice. A large mass of evidence bearing on this point was obtained by the Royal Commission of 1894 on explosions from coal-dust in mines, and a *précis* of it has been made as being valuable from both the historical and the scientific point of view.

Evidence of Witnesses, from the Report of the Royal Commission, Published in 1894.

Prof. Wm. Galloway* commenced to investigate mine explosions in 1870 as H.M. Inspector of Mines: he became an inspector for that special purpose. He found that in many cases the usual explanation of gas explosions was quite untenable, and that all *big* explosions took place in dry and dusty mines. Out of 60-80 cases which he investigated in Scotland, the only big explosion occurred at Nitshill and this was the only dry mine of the lot. He made experiments in 1875 and 1876 and read a paper before the Royal Society in March, 1876, giving in detail the results of his experiments and his views on the influence of coal-dust in colliery explosions. His view at that time was that a mixture of air and fire-damp, which was not ignitable or explosive, became so by the addition of coal-dust. Later, in 1880, he came to believe that the finest dust of all kinds of coal (with the possible exception of the driest kinds of anthracite) are inflammable or explosive when mixed with air alone. He believed that fineness had more to do with it than the quality of the dust. His explanation of why there were no dust explosions at the face, was that there was not sufficient dust there.

* See also *Proc. Roy. Soc.*, 1876, xxiv. 239.

Mr. Fenwick, however, pointed out from experience that the workings were sometimes so dusty that it was scarcely possible to see a man there until you could touch him. Large explosions nearly always spare the workings and the return airways; they follow the main haulage roads, which have the most dust and the freshest air, and seem to avoid the return ways which have bad air and contain gas but are free from dust.

Mr. Scott in his report on the Staffordshire district said, in opposition to this, that the return ways are more dusty than the intake ways, while Mr. Dickinson also stated that in Lancashire mines the return ways are the dustiest.

Mr. W. Morgan, in describing a fire-damp explosion at Edford colliery, said that ignition took place at the furnace and travelled back through the return way where the road was very dusty. But some 40 yards beyond the exit roadway the traces of the explosion ceased altogether.

The following comment was made by the Commissioners on accidents in mines, with regard to Mr. Galloway's experiments and views:—"In emphasizing this claim Mr. Galloway does not appear to have realised the fact that, if dust were the principal agent in coal mine explosions, every blown-out shot occurring in a dry and dusty mine should actually be attended by a more or less disastrous explosion and conflagration, and that, looking at the enormous amount of powder used in mines and the not inconsiderable proportion the blown-out shots must constitute . . . . . disastrous explosions would be of more than daily occurrence if his views were correct."

Mr. John Williamson had had 57 years' experience (dating back to 1834) at the Houghton pit, a very fiery seam, where all the roads were dusty—"full of dust." There had been many explosions but they always occurred at the face where it was not so dusty. He had fired hundreds of shots in very dusty places and had seen many blown-out shots in dusty places, but never the slightest sign of the dust taking fire.

"*In those days they were not so particular about ventilation; they had not so much air in the pits as now.*"

Mr. James Lucas, from his own experience, described three explosions, one extending 50 yards, the second a little longer and the third as much as 500 yards. All were violent and only stopped when they reached a wide part where there was room to expand. In every case the roads were dusty. He said "the explosions were too rapid to raise dust in front of them; *it was the dust already in suspension in the air that caused the explosion.*" He added "In the North Staffordshire deep mines you cannot see 6 feet before you in the return ways" (on account of dust).

Mr. Thos. Lishman described an ignition of coal-dust in his mine. The whole section of the gallery was filled with flame from a blown-out shot and the shock was felt 2,000 feet away. But although the ways were dusty no explosion or extended ignition took place and the men were not killed or even badly hurt. He concluded that the *better the ventilation the greater was the danger*, because of the large current of air in the airways.

Mr. W. N. Atkinson said the roads mostly left untouched by an explosion were the return airways. At Seaham, Trimdon Grange, Tudhoe, Udston, and Elemore the return roads were not dusty. At West Stanley some of them were dusty, and at Mossfields there was dust all over the intakes and return ways alike. At Altofts some of the returns not traversed by the explosion were dusty. He considered the factors essential for an ignition to be a certain quantity of *fine* dust, purity, means of ignition and fineness, perhaps the most important element. He believed the dust ordinarily floating in the air was *harmless*(!), as there was not a sufficient quantity to be inflammable by itself; also his opinion was that the kind or quality of coal from which the dust was generated was immaterial in a dust explosion.

Mr. J. B. Atkinson stated that the violence of an explosion is always greater in haulage ways than at the face. He had heard of only one coal-dust ignition at the face and the evidence for this was doubtful. He knew of several cases in which the explosion was not propagated down or along dusty ways and explained this by *assuming* that the dust was not pure.

Sir H. Hall believed that the dust in the haulage ways was the most dangerous. He had not tried dust from the face nor had he personally known of a single explosion caused by a blown-out shot at the face.

Mr. Joseph Dickinson said "I have had hundreds of explosions under my observation but I never knew of an instance where an explosion could be attributed to coal-dust alone."

Mr. J. D. Isaac stated that a large amount of dust is produced at the faces by the working of the coal. His experience was that a flame usually follows a blown-out shot, but, although he had had many blown-out shots, the dust had never ignited.

Mr. Samuel Wood had the following indirect question (5190) put to him: "We have had evidence to-day, for instance, from one of the officials of the Federation of the North, to the effect that in the Seaham explosion the ventilation was so good that it was absolutely impossible to suppose there was any gas at the time of the explosion. Yet a very dangerous explosion took place." His comment was: "Of course, we have had the same experience in our Lancashire collieries during the last twenty years, in a very remarkable way. *It so happens that where we have had the most fierce explosions the mines have been the best ventilated.* I am now speaking of the 9 foot mines such as Moss pits, Bryan Hall, the Queen pit, and a number of others." He added that he had seen no sign of dust being ignited by a blown-out shot. At the face the dust was purer though not so fine. "Most explosions have originated at the coal-face, and that being so, if dust would ignite at all it would be the kind lying about the coal-face."

The above personal evidence as to the relative safety of the return ways, etc., is substantiated by the information gathered from the reports of various colliery explosions and the reports which the Royal Commissions published in 1894 and 1909.

Extracts from Reports on Colliery Explosions.

The following disasters were caused by shot-firing:—

Seaham, 1880 (164 lives lost).—The explosion was caused by coal-dust, ignited by an ordinary (not blown-out) shot 150 yards from the intake shaft. It was confined to the main haulage ways and did not reach any part of the mine where there was any gas. The ventilating current was 60,000 cubic feet per minute.

Tudhoe, 1882 (37 lives lost). All the men found dead in the intake ways had been killed by the violence of the explosion, whereas those in the return ways had been burnt but had not experienced violence. The air ventilating current was 174,600 cubic feet per minute.

West Stanley, 1882 (13 lives lost).—All the men killed were found in the intake ways. The ventilating current was 63,600 cubic feet per minute.

Trimdon Grange, 1882 (74 lives lost).—All the men killed by violence were found in the intake ways quite near to the downcast shaft.

Risca, 1880 (120 lives lost).—The explosion, caused by four shots, originated in the intake 200-300 yards from the shaft. The ventilating current was 60,000 cubic feet per minute.

Altofts, 1886 (22 lives lost).—See page 77.

Elemore, 1886 (28 lives lost).—This was entirely a dust explosion which was probably originated by a shot fired in the main intake road.

Udston, 1887 (73 lives lost). This was a gas explosion followed by a dust explosion; the men were killed about 10 feet from the intake shaft. The mine was well ventilated.

Camerton, 1893 (2 lives lost).—This explosion was caused by a blown-out shot fired in the intake haulage way. The colliery had been worked for over 100 years and no explosion had occurred hitherto. *During the twelve months previous to the explosion the ventilation had been increased.* At the spot where the ignition started, waggons had been scraping the roof, fresh coal being knocked off and ground up by the wheels. No trace of fire-damp could be found at the spot after stopping the ventilation for a week. Two men placed a couple of shots. The first did the work effectually and then they cleared the dirt away, which would take an hour or more; the second shot was then probably fired. The men, in a refuge hole near by, with their candles, must have seen the ignition and attempted to escape. They left their candles and were found about 20 yards from the refuge hole. There was no violence at the point of origin; the violence became greater as the distance increased. At about 1,180 yards from the origin, two doors were blown into fragments and the door posts shattered as if a violent explosive had been fired right into them, the iron framing of the doors (1¾ inches by ½ inch) being broken in two.

The increase in the ventilation during the preceding twelve months had made the road drier. Where the explosion ended there was a stretch of 80 yards of wet road. In one place the explosion had jumped 53 yards of wet road. The manager did not consider the pit dry and dusty. Moreover the coal-dust was not fine; it was mixed with shale-dust and was so heavy that it did not float away on being disturbed.

Brancepeth, 1896 (20 killed).—A shot fired on the main engine plane ignited the coal-dust: the mine was not considered dry or dusty.

Tylorstown, 1896 (57 killed).—A shot, fired in a stall, ignited gas; the effects due to the after ignition of coal-dust were far reaching.

Drumpeller, 1898 (4 killed).—Due to a gunpowder shot fired in the haulage way.

Brandon, 1900 (6 killed).—A shot fired caused a gas explosion which was extended by dust.

Orrell, 1901 (4 killed).—A shot, fired on the haulage road, ignited dust and the explosion travelled throughout the roads.

Universal, 1901 (81 killed).—There was some doubt as to the cause of this though it was probably due to a shot. The explosion travelled throughout the mine except the return airways, which were dry and dusty: everyone in the mine, except one person, was killed.

Llanbradach, 1901 (8 killed).—A shot fired on the main intake ignited dust, although no fire-damp was present. The explosion was very extensive, but fortunately only 14 men were in the seam at the time.

National, 1905 (119 killed).—A shot ignited some fire-damp and the explosion was propagated by dust.

Wingate Grange, 1906 (24 killed).—A shot fired in the main haulage caused a dust explosion.

Urpeth, 1906 (4 killed).

Dinas Main, 1907 (7 killed).—A shot of gunpowder on the main haulage way initiated a coal-dust explosion.

Whitehaven, 1907 (5 killed).—This was due to fire-damp ignited by a shot.

Washington Glebe, 1908 (14 killed).—An explosion of fire-damp together with coal-dust.

Norton Hill, 1908 (10 killed). Due to coal-dust ignited by a shot.

Evidence of an entirely similar nature has been obtained from investigations of the causes of coal mine explosions in other countries. In the United States, the greatest coal producing country in the world, the coal-dust factor attracted scant attention until 1907, when the total death roll in one year from so-called "windy shots and powder explosions" reached the appalling figure of 1,148.

Mr. Rice, who summarised the results of these explosions, said, with regard to them, that these powder and windy shot explosions are, in reality, dust explosions. "It is true that these generally originate from blown-out shots, but it is, without question, coal-dust that carries the flame, and death in its trail."*

The following were some of the dust explosions that occurred in a *single year* (1907) in the United States:—

Date.	Place.	Killed.
Jan. 23	Pimero	24
,, 28	Penco	12
,, 29	Stuart	90
Feb. 4	Thomas	25
Dec. 1	Naomi	35
,, 6	Monongah	358
,, 16	Golande	56
,, 19	Darr	230

All these explosions occurred in winter, when the mines are driest.

1909 REPORT OF THE ROYAL COMMISSION.

The second report (published in September, 1909) of the Royal Commission on Mines, which was appointed in June, 1906, deals with practically all the causes of accidents in mines, together with many other matters of great importance in mining. The number of questions in the minutes of evidence exceeds 50,000, and the whole forms a very complete and up-to-date investigation into all the risks and dangers of coal mining, together with the factors that make for increased safety, these ranging from the education of the officials to the methods of rendering coal-dust innocuous. Of the twenty-one sections that comprise the Report, only two bear directly on the coal-dust question, viz., Part V., on ventilation, and Part VII., on coal-dust explosions.

Most of the points dealt with in Part V., except those questions relating solely to the machinery, have already been considered, more especially in chapters IV. and V. on Respiration. The fundamental phenomena that underlie the subject matter of Part VII. are discussed in chapters VI.

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* Galloway, *Trans. Inst. M. E.*, 1912.

and VIII. and the present chapter, but there remain some important points, in connection with coal-dust, that have not yet been considered. These include the source and occurence of coal-dust, the methods of preventing accumulations of it in mines, its removal and the methods of rendering it non-ignitable.

SOURCE AND DISTRIBUTION OF COAL-DUST.

Most of the witnesses were of opinion that inflammable dust is usually confined to the roads, more especially to the main haulage roads, and that the dust existing at the face is often so coarse or so mixed with shale and stone-dust as to be non-ignitable.

Dust originates from the following causes:—(1) the screens, (2) falls from badly constructed tubs, (3) falls from over-filled tubs, (4) particles blown from the top of tubs in the haulage, when travelling against the air-current, (5) particles blown from tubs in the shaft, (6) traffic of men and horses, (7) grinding of the coal-seams in the roof and sides of the roads, (8) small coal left in the tubs, (9) action of the ventilating current in bringing dust from the faces into the return airways, and (10) the action of high explosives.

The methods of preventing screen dust from entering the downcast shaft are: (1) removal of the screens to a distance, (2) drawing off the dust in a cyclone or similar separator and allowing it to settle, (3) moistening the shaft or indrawn air, to precipitate the dust. One of these means should be adopted at every colliery, and for new collieries method (1) appears to be the best. Method (2) is already in practice at one or two places. One of the first to utilise this device was Mr. W. H. Chambers at Cadeby pit and undoubtedly it is a most efficient and economical method of dealing with the difficulty, as the dust is recovered and can be sold, or used at the boilers; there is certainly very little, if any, coal-dust from the screens, or from any other pit-head source, entering the intake shaft at Cadeby. It would probably pay to introduce the method at all screens, even at those which are a considerable distance from the downcast. If some such collecting device is not employed, the coal should be wetted by fine water sprays before it goes on to the screens.

Moistening of the air in the shaft (method 3), to precipitate dust, would be very objectionable if applied to the majority of dusty mines during warm weather. The mines are already very warm and by wetting the intake shaft the wet bulb temperature would be raised considerably. In shallow damp mines it is probably more practicable, but each mine must be considered on its own peculiarities.

It is most important in dry mines to have the tubs kept in good condition and not over-loaded, as coal dropping on the roads from defective tubs is a very fruitful source of dust. If a convenient closed tub could be devised, it would do much to diminish the dust in the haulage roads. One way of dealing with the difficulty is to wet the coal in each full tub before it starts on its journey; this method is in use in many pits. In warm pits it might easily do more harm than good by affecting the health of the men, but in pits where the temperature is below 70° F. it appears to be an excellent method of preventing accumulations of dust in the haulage ways, and should be adopted wherever practicable.

As regards the removal of dust, in many well-managed mines this is not necessary as the accumulations are not excessive, but in most dry mines there is more than enough to propagate explosions unless it is considerably diluted with stone-dust. Some of the dangerous dust can be removed by increasing the air current for a few minutes, so as to lift the dust and blow it out of the pit, this being done at week-ends when no men are at work in the mine. Such a method, provided the pit was empty and no source of ignition was possible, would be well worth trying. To remove the week's accumulation on Saturday or Sunday seems an excellent plan, and it could be followed by stone dusting on Monday morning. There is much to be said for such a method, as it is just the fine dust, *put into the air by the reversal of the air current* at the ignition stage, that gives the fuel for the propagation of the explosion.

A *reversal of the ventilation* at week ends, when men are out of the pit, would be still better than increasing the speed of the fan. A constant or regular brushing up of dust from the floor, roof, and sides, *when the pit work is in full swing*, should not be allowed. Such a proceeding certainly greatly increases the risk of an explosion spreading, if there happens to be an ignition; and, of course, the more men, the more lamps, etc., therefore the more chance of an ignition of gas, of dust, or of *gas and dust*. The periodical reversal of the ventilating current as a means of prevention of explosions in mines, first suggested by the author,* will be considered in rather more detail under the section "Prevention of Explosions."

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* "Gob-fires and the Prevention of Gob-fires in Mines," *Trans. Inst. M. E.*, vol. xliv., part 2.

CHAPTER VIII.

COAL-DUST EXPLOSIONS: PART II.

THE PHENOMENA OF DUST EXPLOSIONS.

A good example of the course of a pure dust explosion, with no gas present, is provided by the Altofts disaster of 1886, the details of which were recorded in full. The ignition took place on a main haulage way, which was also a main intake for fresh air. It was caused by the last of three shots which were fired to remove some rock. This third shot was, judging from the results, over-charged and blew out the stemming. The dust was ignited and the ignition developed into a violent explosion, which traversed practically all the intake roads that had any dust, but did no damage at any of the working faces or in the return airways.

At the spot where ignition occurred, and for 50 to 70 yards, there were no signs of violence; the men found dead in this part had been burnt and suffocated. After 70 yards there were signs of violence, the wave of progressive combustion having increased in force the further it travelled. This was evidenced by the props blown out, the huge falls of roof and the fact that the dead bodies in this region had broken backs and limbs.

Still further on the explosion had attained enormous speed and violence. Tubs had been smashed to matchwood, men had been literally blown to pieces and heavy machinery had been dislodged in a way that indicated a speed of 50 miles or more per minute.

These three shots were the first fired on any intake haulage road in the mine since the colliery started 23 years before. The mine was well ventilated, with a total of 147,000 cubic feet of air per minute, of which 50,000 were passing along the road where the ignition occurred. Mr. Garforth (one of the managers) said: "We try to get the ventilation right to the face, or, as we say, right on to the men's backs."

All big dust explosions are similar to the one at Altofts. Ignition is followed by quiet combustion for 50-100 yards, then the wave of progressive combustion gathers speed and finally attains a velocity approaching that of detonation and races through the dust and air at a speed of 50-100 miles per minute.

Such dust explosions always proceed *against* the current of air; sometimes they go the other way also, but seldom reach the working faces. As a rule the branch of an ignition which travels with the air current fails to develop violence. Almost without exception dust explosions originate in and are confined to intake haulage roads which are dry and dusty. They seldom traverse the working-faces or the returns although many of these are also dry and dusty.

A stretch of damp road 100 yards or more in length will stop the explosion, probably because there is not the minimum amount of dust necessary to propagate it already present in the air. Also a shorter stretch of road covered with stone dust will stop the explosion provided the stone dust is pure and fine.

In a big coal-dust explosion there are many phases lying between these two extremes of ignition and the final explosive velocity. The first phase, the ignition, does not necessarily develop into a violent explosion: we know from mining records that there have been many dust ignitions which did not grow into explosions, but on the contrary died away after passing over 50-100 yards. Such ignitions often do little if any damage. It appears that they are sometimes pulled up (see evidence of J. Lucas, page 68) when and if they arrive at a place where the air has room to expand.

At other times, however, the ignition, instead of dying away, develops into an explosion which travels through miles of roadway, increasing in speed and violence the further it goes and is only pulled up at the top of the pit, or by a stretch of wet road or a layer of air which contains too small a percentage of oxygen to propagate it. There is evidence, too, that an explosion can wane and wax again; at cross roads it sometimes appears to be retarded and then to start afresh on the road or roads beyond.

In order for ignition to take place there must be a large excess of dust, much more than can be burnt completely to carbon dioxide and water by the air that is mixed with it. By reason of this excess of dust the ignition stage is not violent; a large quantity of carbon monoxide is formed and the reaction, $2C+O_2=2CO$, does not give off a relatively great amount of heat. This quiet, slow combustion does, however, evolve some heat; the temperature gradually rises and with it the speed of the reaction, until a point is reached when the wave of progressive combustion overtakes the wave of compression* (or "pioneering" wave) which moves in front, throwing up the dust.

If this happens the character of the combustion is entirely changed. The dust is no longer in large excess but may be in about the right proportion to burn to carbon dioxide and water, in which case a violent explosion occurs. If the air in the rest of the mine is mixed with sufficient fine coal-dust (and very little is required) the conditions are favourable for the transmission of this *explosion* and it races through the roads at a rate of 50-100 miles per minute.

In the series of experiments in the Altofts tube there was, apparently, only one instance in which the combustion wave overtook the wave of compression. When this happened, three sections of the tube were torn to pieces and flung with enormous force in all directions. Obstacles in the path of the ignition invariably increase the speed and violence of combustion. This is because such obstacles retard and reflect the wave of compression and thus the combustion wave overtakes it sooner.

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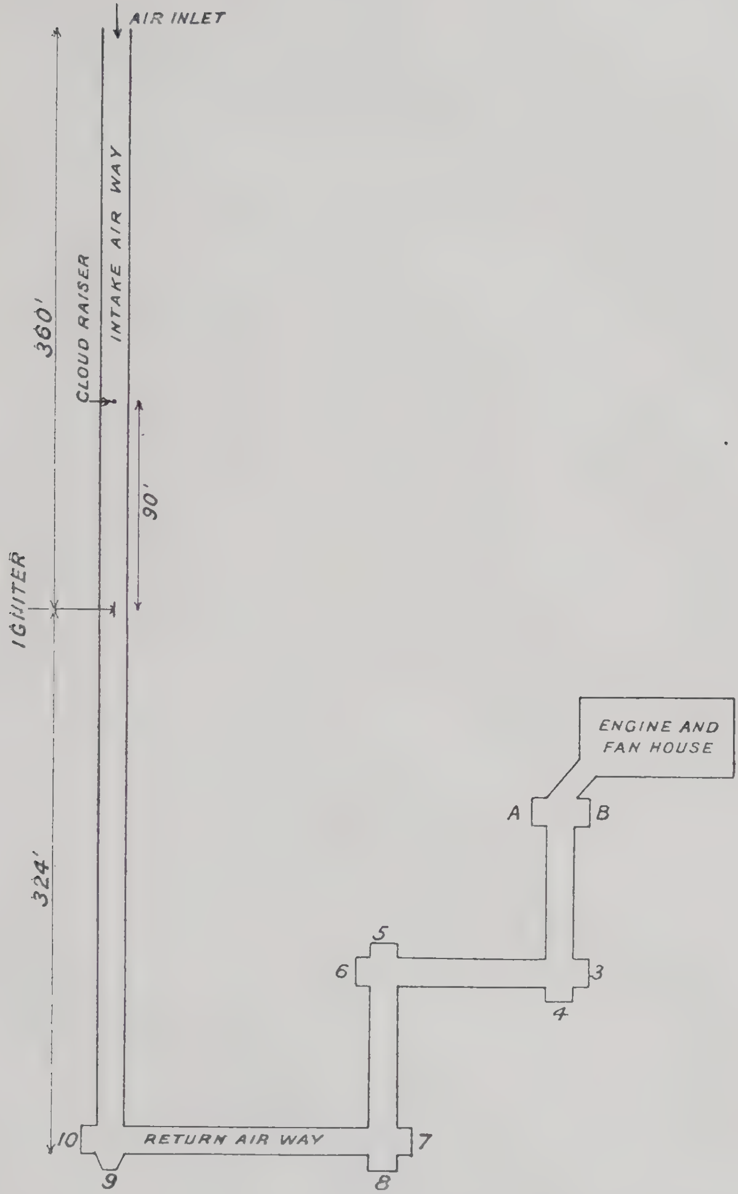
* These two different waves were distinctly seen in the numerous experiments carried on at the Altofts tube, and also by M. Taffanel in the course of his work ("Essai sur les Inflammation de Poussières"). The wave of compression was first recorded by W. C. Blackett, who called it the "pioneering wave" ("The Combustion of Oxygen and Coal-dust in Mines,") *Trans. Inst. M. E.*, 1894, vol. vii., page 54).

From this account of the phenomena it will be gathered that the conditions required for an *ignition* are quite different from those necessary for a violent *explosion*. In order that an ignition may take place an excess of dust must be present, but a violent explosion requires only about the amount of dust needed for complete combustion. An explosion will not traverse a region containing excess of dust with increasing velocity but will slow up to the ignition pace: it will not, however, be stopped altogether. On the contrary, a mixture of dust and air containing too little dust to be ignited by a flame or shot will propagate an explosion, started elsewhere, if a sufficient degree of violence has been attained.

A curious phenomenon noticed after a big dust explosion is that coked dust is found plastered on the sides and top timbers and on the floor, this coked dust being on the sides *opposite* to the ones facing the origin of the explosion (except on the timbers near the origin where it may be plastered on either side or on both). The explanation of this is as follows: when the explosion wave passed, there was no coked dust to be plastered. The wave whirled up clouds of dust into the air *behind* the explosion and this dust was then burnt to carbon monoxide and coked dust, which was driven on to the timbers by the return wave, due to the contraction of the gases by cooling, or by a return wave similar to that which is often observed in gas explosion experiments.

Experimental Explosions.

In quite recent times large scale experiments on coal-dust explosions have been carried out in England, France and the U.S.A. These experiments are being continued, the station in England having been removed from Altofts to



Plan of Altofts Plant (diagramatic).

Eskmeals in Cumberland. In France the work has been transferred from Liévin, where it was begun, to an actual mine at Commentry. The results obtained so far are of relatively little use to colliery managers, chiefly because the experimental conditions have not been made to approximate closely enough to those which hold in actual practice.

The experiments performed at Altofts are so well known to mining people that they need not here be considered in detail; it will be sufficient to give a brief summary of them. They were conducted in a plant designed by a committee of mining experts, assisted by a staff of scientists, the cost being borne by the Coal Owners' Association.

The plant consisted of an intake tube 7½ feet in diameter, made of old boiler shells 24-30 feet long, rivetted together, the total length being 600 feet in 1908. It had a concrete floor 5 feet wide, in which sleepers and rails were fixed. The return tube was constructed similarly, but was 6 feet in diameter and 295 feet long, and was made zigzag, with explosion doors, etc. (which could be blown-out), in order to protect the fan.

The coal-dust mostly used was got by disintegrating Silkstone nuts and was made to approach the screen dust at Altofts Colliery in fineness. The following table shows the relative composition and degree of fineness.

DUSTS USED AT ALTOFTS STATION.

	Screen Dust.	Artificial.	From Haulage-way.		
			Floor.	Sides.	Bars.
Composition—					
Moisture	4·42	3·21	8·12	9·05	7·87
Volatile matter	24·75	33·68	25·10	22·40	20·30
Fixed carbon	62·99	57·60	40·24	39·95	35·93
Ash	7·84	5·51	26·54	28·60	35·90
Degree of fineness—					
On 100* sieve	Nil.	7·25	47·3	6·2	1·7
Through 100 on 150 sieve ...	Nil.	7·50	17·1	4·1	1·3
Through 150 on 200 sieve ...	Nil.	3·00	1·9	0·1	0·8
Through 200 on 240 sieve ...	0·3	9·25	6·7	6·9	5·1
Through 240 sieve	99·7	73·00	27·0	82·7	91·0

* Number of holes per linear inch.

From this table it will be seen that the dust used was much purer than the mine dust. It is doubtful whether dust of this composition is ever found in the intake haulage way of any mine, consequently the results obtained from it are not applicable to actual mining practice.

The dust was strewn over the road of the intake and on shelves at the side, in the proportion of 4 ounces per cubic foot of air space. Ignition was produced by the discharge of a cannon containing 24 ounces of blasting powder, and, as the Report states, "This will generally give a successful ignition. Sometimes, however, it did not, so to prevent disappointment to visitors a cloud raiser was employed, this being a small cannon with 4 ounces of powder, which was fired 90 feet nearer the intake end and 2 seconds before the larger cannon."

After spreading the dust the fan was started, the doors of the fan drift being wide open until the correct amount of air (60,000 cubic feet per minute) was passing. Then the fan drift doors were closed and the air sucked through the intake. The closing of the doors rang a bell in the firing station, and after seven seconds the small cannon was fired, and the large cannon two seconds later.

Surveying the results obtained, one is struck with the very great difference between them and the phenomena of actual dust explosions in mines. For instance, in many of the experiments at Altofts there was almost as much violence in the return as in the intake part of the tube. Moreover, in an experiment with anthracite dust there was no propagation towards the intake but a considerable amount of flame in the return; such a phenomenon has never been observed in a dust explosion in a mine.

Clearly the mistake made was in the method of depositing the dust. The tube should be large enough to allow of a square section inside, should have projections on the roof, walls and floor, and should contain props and bars as in an actual mine. The dust should be put into the airway by the air-current and be deposited behind the projections as is the case in actual practice. What the designers of the Altofts experiments evidently regarded as unimportant details are, as a matter of fact, essential conditions.

The chief facts established, or, rather, *claimed* to be established by these Altofts experiments, are:—

(1) Pressure increases with the distance travelled by the explosion.
(2) Obstructions have a marked influence in causing the explosion to be propagated with greater violence.
(3) Fine stone-dust, mixed with the coal-dust, has a restraining influence.
(4) It is possible to propagate an explosion through a cloud of wood charcoal in air.

The first three of these "facts established" were merely confirmations of what was well known previously, hence the net result of this series of experiments is the conclusion that an explosion may possibly be propagated by a cloud of charcoal (probably containing a large amount of occluded air)—a conclusion that is not likely to be of much use to managers of coal mines.

In the experiments made in France and in the United States, there was a similar want of attention to essential detail, and the results obtained hitherto are of comparatively little value. At Liévin it was found that the combustion wave could be destroyed by putting water or non-inflammable ashes (120 litres of water or 400 litres of ashes per square metre section of the roadway) into the air, by means of the first wave of the explosion. But this contrivance the so-called Taffanel barrier—failed to pull up the explosion at La Clarence Colliery on September 3, 1912.

The following quotation indicates the method of experimenting used in the United States:- - "In the afternoon the final explosion at Bruceton mine was effected. Fifteen hundred pounds of dry coal-dust had been placed in the bore, and 5½ pounds of black powder had been planted at the face of the mine, on the inner end and at a cross-cut half way in the entry. From the mouth of the mine a sheet of flame, estimated at 150 feet in length, shot out over the ravine. Trees were withered near the entrance, three coal cars were blown hundreds of feet and ties were wrenched out. It was found that an 18-inch stopping had been blown out, but the Taffanel barriers had stopped the explosion in the return air passage. The force of the explosion had lifted the dust and carried it along the air passage, causing the flame to die out. So great was the force generated that two wooden piles, each half a foot in diamter, 50 feet from the mouth of the mine, were broken off at the ground, and a car loaded with 1½ tons of slate was hurled 450 feet across a ravine. The concrete work inside the mine was lifted 8 inches and cracked and seamed for over 100 feet, while a pool of water was lifted in its entirety, carried round a corner and deposited in a depression 25 feet from its original position. It will require about six months for the mine to be repaired."*

It is needless to criticise experiments of this kind; they are entirely valueless.

INFLUENCE OF THE QUANTITY AND QUALITY OF DUST.

Working at the experimental station at Pittsburg, Mr. G. S. Rice† estimated that bituminous coal-dust, that has passed a 200 mesh sieve, will form an explosive mixture when the proportion is 1 pound of dust to 500 cubic feet of air. For complete combustion 1 pound of this dust requires only 133 cubic feet of air.

It was found by Taffanel and Durr (third series of experiments) that, even under very favourable conditions, using very inflammable dust and a large flame from a benzine torch, the minimum density at which ignition took place was about 200 grams of dust per cubic metre (*i.e.*, about 1 pound per 80 cubic feet). But when dynamite was used, ignition occurred with 46 grams per cubic metre, or 112 grams per cubic metre if the dust was not previously in suspension.

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* *Colliery Guardian.*

† U.S.A. Bureau of Mines. Abstract *J. S. C. I.*, 1911, page 943.

The dust present in the air of even very dusty galleries, and that stirred up by the traffic of the mine, is usually too small in quantity to cause dangerous results with an open light. It is only under special circumstances (*e.g.*, the breaking of a haulage rope and consequent running away of tubs) that a cloud of dust might exist dense enough to be ignited by a flame. The Monongah explosion in 1907 was caused by a runaway train of tubs; this set up a thick cloud of dust, which was ignited by an arc light, and 358 men were killed.

As to the influence of the quality of the dust, experiments have been carried out by Bedson, Taffanel and Durr, and by the Committee on Explosions in Mines.

Bedson and Windus* in 1906 showed that it was possible to get ignition of coal-dust and air by means of a small luminous flame. Brown coal-dust ignited very readily, bituminous dust less easily and anthracite dust not at all. Using a bunsen flame instead of the luminous flame, even the anthracite dust ignited, but the ignition was merely local and was not propagated throughout the mixture, as was the case with dust from brown coal.

In 1907 Bedson showed that different qualities of coal-dust varied widely in their behaviour. He also found that the tendency to ignite was increased by previously drying the dust at 100° C., and was diminished by long standing or by mixing with inert material.

In 1910 he† pointed out that the ignitability of any particular dust depended largely on its degree of fineness.

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* *T. I. M. E.*, 1906, vol. xxxii., page 529; 1907, vol. xxxiv., page 91.

† *T. I. M. E.*, 1910, vol. xxxix., part 5.

A sample was divided into four fractions by means of sieves of 120, 150, and 200 meshes; the minimum current required to ignite each of these (by a hot wire) was found to be 12, 10·5, 10·25, and 9·75 ampères repectively.

In this paper Bedson also showed that the most inflammable part of the coal is the part that is soluble in pyridine. While the original coal required 11·5 ampères, the pyridine extract required only 10·5 ampères; the insoluble residue did not ignite even with 15 ampères. Thus the pyridine extract behaves like a brown coal, while the insoluble portion resembles anthracite in its behaviour, as might have been expected.

This result was confirmed in 1912 by the investigators at the Eskmeals station, though curiously enough they put it forward as an independent observation, even while referring to Bedson's apparatus. And although Bedson obtained his results by examining only one variety of coal, his method is the more convincing in that he actually separated the two constituents and determined the relative ignitability of each.

Taffanel and Durr, at Liévin, estimated the relative inflammability of dusts by means of a porcelain tube 10 centimetres long and 25 millimetres internal diameter; this was placed vertically and heated uniformly to a measured temperature. A definite weight of the dust, ground to uniform fineness, was projected into the tube from above by a blast of air, and the dimensions of the flame were registered photographically. It was found that lycopodium inflamed at 590° C., starch at 500° C., and sugar at 460° C., while with coal-dust no flame was produced as a rule below 775° C.

Coke-dust gave no flame but a shower of red-hot particles. It was suggested that the presence of volatile matter in the dust is a necessary factor in the production of flame. This suggestion has, however, been proved to be misleading, since charcoal powder can cause flame.

RESULTS OBTAINED BY THE COMMITTEE ON EXPLOSIONS IN MINES.

The second report (published October, 1912) of the Committee on Explosions in Mines deals with the relative inflammability of coal-dusts. The various dusts were made by grinding the coal, sieving through a 240 mesh sieve, and drying for one hour at 110° C.

A platinum spiral, which could be heated electrically, was wound round a silica tube inside which was the junction of a pyrometer. The relative ignitability was determined by blowing 2 grams of the dust with a measured quantity of air across the heated spiral.

It was found that the temperatures at which the platinum coil ignited ordinary dusts varied from 995° C. to 1,105° C. except in the case of anthracites; these did not ignite below 1,400° C., the limit of the trials. Using the same apparatus and method, the ignition temperatures of several other substances were determined, with the following results:—

Sulphur	340° C.	Starch (maize)	980° C.
Gunpowder	550° C.	Starch (wheat)... .	995° C.
Lycopodium	940° C.*	Starch (potato) ...	1030° C.
Sugar	980° C.*		

The Committee also tested dusts in an apparatus somewhat similar to that used at Liévin: the ignition temperatures obtained with this were much lower than those got by using the heated spiral of platinum. They also found that on putting a copper gauze *inside* the hot tube, ignition occurred at a much lower temperature, a result that would, of course, be expected.

Using a dust that inflamed at 1,055° C. with the platinum spiral, the following figures were obtained:—

Time of fall of piston.	Porcelain tube empty.	Porcelain tube containing copper gauze.
12 secs.	840° C.	760° C.
35 secs.	820° C.	690 C.

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* Compare page 87.

These figures illustrate how enormously the temperature of ignition is influenced by the method employed for causing ignition.

In this report some experiments are described on the effect of inert dusts mixed with the coal-dust. A coal-dust (227 N, containing 4 per cent. ash) which ignited at 1,005° C. with the platinum spiral was mixed with various non-inflammable materials and the mixtures tested with the same apparatus, the following results being obtained:—

Mixture.	Ignition Temperature.
96 parts coal dust with 4 parts shale dust ...	... 1025° C.
92 ,, ,, ,, 8 ,, ,, ...	... 1045° C.
90 ,, ,, ,, 10 ,, ,, ...	... 1045° C.
80 ,, ,, ,, 20 ,, ,, ...	... 1095° C.
95 ,, ,, ,, 5 ,, calcium carbonate	... 1025° C.
90 ,, ,, ,, 10 ,, ,,	... 1035° C.
85 ,, ,, ,, 15 ,, ,,	... 1045° C.
80 ,, ,, ,, 20 ,, ,,	... 1095° C.
98 ,, ,, ,, 2 ,, sodium bicarbonate	... 1075° C.
96 ,, ,, ,, 4 ,, ,,	... 1095° C.

In the experiments in which sodium bi-carbonate was used no real propagation of flame through the dust cloud occurred; the temperatures stated above are the minimum values at which a pronounced burning of *part* of the mixture (round the igniting coil) took place. It might perhaps be more correct to say that no ignition occurred at the highest temperature that could be employed (1,400° C.), for even at this temperature there was no general inflammation of the dust cloud.

The effect of the sodium bi-carbonate is, no doubt, due to the evolution of carbon dioxide and water vapour, which lowers the percentage of oxygen in the air around the coil; moreover, carbon dioxide has a great restraining influence on the ignition of coal-dust. The importance of these two factors was pointed out by the author in an earlier paper (T.I.M.E., vol. xliii., pt. 2, pp. 132-166). In this paper it was shown that a slight reduction in the percentage of oxygen in the air greatly reduces the ignitability of a coal-dust, and that the addition of 1 part of carbon dioxide has as great a retarding effect as about 14 parts of nitrogen.

In this particular instance, where sodium bi-carbonate is used, there are the additional considerations that the temperature is reduced, owing to the formation of gaseous carbon dioxide and water from the solid state, and also to the decomposition of the bi-carbonate itself.

The Committee also found that the ignition temperature of methane in air lies between 650° and 750° C., and that an increase in the oxygen contents of the air lowered the ignition temperature of dusts.* A gentle stream of oxygen was allowed to pass up the tube just before puffing the air through it; in this enriched atmosphere the dust, which inflamed at 840° C. in the heated porcelain tube,† ignited at 560° C. A semi-anthracite dust ignited at 600° C., an anthracite dust at 780° C., and wood charcoal at 750° C.

The wood charcoal had been treated with chlorine at 1,000° C. and then heated in a vacuum for four days at 1,100° C., yet it gave a distinct flame. This shows that once inflammation has been effected the presence of volatile matter is *not essential* for the production of flame.

Altogether some fifty varieties of coal-dust were tested in addition to dusts from sugar, starch, lycopodium, flour, gunpowder, and sulphur. In reviewing their results, the Committee say:—"It is impossible to trace any relationship between the percentage of volatile matter in the coals and the relative ignition temperatures of their dust clouds."

Their summary is as follows:—

> "A method is described by which the relative inflammability of different dusts can be ascertained by measuring the temperature of a platinum coil which just ignites a uniform cloud of dust and air projected across the coil fixed in a glass tube. It is shown that the relative inflammability does not depend on the "total

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* See, however, page 22, Mallard aod Le Chatelier's work.

† 1065°C with the platinum spiral.

> volatile matter," but on the relative ease with which inflammable gases are evolved.*
>
> "The order of inflammability so obtained corresponds in a remarkable degree with the percentage of inflammable matter extracted from the same coals by pyridine.
>
> "We are of opinion that these two methods form a valuable means of discriminating between different coals in regard to the sensitiveness of their dusts to ignition. It must, however, be borne in mind that these tests have been made with dusts artificially ground and sieved to an equal degree of fineness, and since coals differ considerably in their power of resistance to pulverisation, the friability of a coal must be taken into account."

It must be confessed that the report as a whole is very disappointing, seeing how much experimental work was done and under what auspices. It had long been known that ignition temperatures varied widely with the means of ignition employed, and Bedson had already established that the pyridine extract was the most inflammable part of the coal. The other results obtained by the Committee are not likely to be of much service to mine managers in their endeavour to raise the factor of safety in mines.

The experiments were not well devised, the conditions being too remote from those which obtain in actual mining practice. In particular the following criticisms may be made of the more important points:—

(1) *Before being tested the dusts were dried at 110° C. in air for one hour.*

Several investigators have shown that the properties of many dusts are profoundly altered by this treatment. Oxygen is absorbed very rapidly at 110° C. by most coal-dusts and by some more than others.† Also there are indications that occluded methane disappears, its place being taken by carbon dioxide. The ignition temperatures of some dusts, rich in occluded methane and oxygen, are largely altered by this treatment, those of other dusts are lowered by removal of water, while others are hardly changed at all.

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* It should be noted that no evidence is given in support of the latter part of this statement.

† See pages 95, 138, 139.

Moreover, 110° C. is far above the highest temperature of any mine ventilating current. The dusts should have been prepared in the form in which they actually exist in a mine.

(2) *The source of ignition was a hot platinum spiral.*

Platinum is a most objectionable substance to use for causing ignition in these experiments, since it has a profound catalytic influence in inducing combustion. One dust may possess constituents that are easily affected by such a catalytic hot surface, while another dust may not, although in reality they may be of equal inflammability with an ordinary source of ignition such as a flame or a broken arc.

In the case of ignition temperatures of gas mixtures, Dixon and Coward (J.C.S. 1909, 95, 514) have shown how to eliminate the influence of solid surfaces, and some modification of this method might easily have been applied to ignitions of coal-dust in air.

Again, hot platinum spirals are not used in coal mines. The use of such a spiral in laboratory experiments is only legitimate when it is standardised against something that is liable to cause ignitions in a mine.

(3) The conclusion that *the relative inflammability does not depend on the total volatile matter but on the relative ease with which inflammable gases are evolved* shows that there still remain chemists who labour under the superstition that inflammable *gas* must be present for an explosion to take place. And this in spite of the fact that the Committee themselves showed that purified wood charcoal inflames in air rich in oxygen, and it is well known that fine aluminium dust will explode violently with air.

This point, the supposed relation between volatile matter and inflammability, will be considered in the next section.

(4) The Committee seem to have overlooked what many chemists regard as a vital point—the quantity and composi-

tion of the gas occluded in the dust. The Bedson test for occluded gases should always be carried out, if the results are to be of any value in future research.

Supposed Connection between Amount of Volatile Matter and Degree of Inflammability.

Many experimenters and most practical mining men are of opinion that coal-dust is more inflammable and explosive in proportion to the (so-called) volatile matter it contains. It is for instance well known that the dust from brown coal and cannel is more easily ignited than that from bituminous coal, while the dust from this is more inflammable than that from anthracite. And it is equally well known, of course, that the percentage of "volatile matter" diminishes as we pass from brown coal to anthracite.

But it is unscientific to jump to the conclusion that these are necessarily effect and cause. It must not be overlooked that there are other differences between these varieties of coals, notably in the percentages of oxygen they contain and the amount of moisture. In brown coal there is about 28 per cent. of oxygen, in cannel 8-9 per cent., in bituminous about 6 per cent., and in anthracite as little as 1½-3 per cent. There is no doubt that the so-called volatile matter and the oxygen contents are closely related. Which factor is it that increases the ignitability of coal-dust, the proportion of volatile matter or the oxygen contents?

Many people who believe that the volatile matter is the deciding factor go so far as to say that the distillation of this "volatile" matter is an essential step in a dust ignition and explosion. Although they have been converted to the view (and have moreover been the means of converting others to this view) that a mixture of coal-dust and air, in complete absence of gas, can be ignited and can, under favourable conditions, cause an explosion, they are not able to rid themselves of the idea that the mechanism must be exactly similar to that of a gas explosion. Consequently they adopt this distillation hypothesis, which is apparently supported by the fact that the inflammability of a dust is (roughly, at least) in proportion to its percentage of "volatile matter." But the fact that powdered aluminium and some other finely powdered metals, form very explosive mixtures with air, cannot possibly be accounted for by any such hypothesis, although the phenomena of the explosions in these cases are very similar.

In the case of coal-dust explosions there may, in the early ignition stage, be some distillation, mixing of the products with air and final ignition of the gaseous mixture, but it is not likely, and it is inconceivable that this process should take place when the explosions are travelling at the enormous speed of 50 to 100 miles per minute.

Indeed it is neither necessary nor useful to hold any such distillation theory. After what has been shown in connection with the influence of even a small decrease in the oxygen contents of the air, it is for the present, a sufficient explanation to say that it is the fact that brown coal and cannel require so much less oxygen for complete combustion than anthracite (for particles of the same mass) that makes the former ignite so much more readily.*

However, the problem demands fuller research for a satisfactory and convincing settlement.

Another point about coal-dusts which needs further investigation is the cause of the supposed greater inflammability of fresh coal-dusts as compared with old. Some evidence goes to show that dust is more readily ignited when it is fresh. This (if correct) is probably due to the presence of occluded methane, together with oxygen and other gases; a dust containing methane would almost certainly be more inflammable than the same dust after it had lost this gas, but it is also likely that a dust which contains occluded oxygen with other gases, would be quite as inflammable if not more so.

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* Also coals are endothermic, and the more oxygen they contain the more endothermic they are (see page 132), and generally the higher the oxygen contents the higher the calorific *intensity* (in the absence of moisture).

In this connection the evidence given before the Royal Commission by Dr. Bedson may be mentioned. He stated that Ryhope dust gave 36½ cubic centimetres to 66·3 cubic centimetres of gas in vacuo at 30° C., and at 50° C. it gave 116 cubic centimetres of combustible gas per 100 grams. On the other hand, Brancepeth dust, collected from the hopper, where there had been an explosion of dust (ignited by a torch), gave off gas *in vacuo, but this was not combustible gas*: it consisted of nitrogen, oxygen and carbon dioxide.

One hundred grams of dust gave 224 cubic centimetres of gas, which analysis showed to contain, $CO_2 - 0·98$, $O - 18·63$, and N 80·39 per cent. This was very fine dust collected from the top of the hopper. When this dust was heated to 100° C. and the gas sucked off *in vacuo*, it consisted of $CO_2 - 13·65$, $O - 0·64$, and $N - 85·71$ per cent. A sample of the dust collected from the bottom of the hopper gave nitrogen, oxygen and carbon dioxide at 30° C. *in vacuo*, and at 50° C., the same with a little inflammable gas.

It would be of interest to compare the inflammability of fresh coal-dust freed from occluded gas by exhausting *in vacuo*, and of the same dust oxidised by exposure to air for a long time and then also freed from occluded gas by the same means. There is little doubt that the oxidised dust would ignite more readily than the fresh dust.

In connection with the ignition of dust, it must be remembered that much depends on the composition of the air with which it is mixed. This part is dealt with later, in chapter IX.

The Influence of Shot-firing.

The ignition of coal-dust by a blown-out shot is of a different nature from the simpler ignition caused by a flame, an electric spark, or an arc. In most recorded cases in which blown-out shots have caused ignition, the charge of powder was comparatively large, amounting in some instances to two and even three pounds, though the average charge is about one pound. Now the gas from powder is itself inflammable (when mixed with air) and moreover, the quantity produced is very considerable, 2 pounds of blasting powder yielding about 10½ cubic feet.

PRODUCTS FROM BLASTING POWDER.

Composition of Gas.		Composition of Solid.	
By volume.		By weight.	
CO_2	32·15	K_2CO_3	41·36
CO	33·75	K_2SO_4	0·59
N_2	19·03	K_2S	37·10
H_2S	7·10	Sulphur (as polysulphides)	14·11
CH_4	5·24	KCNS	2·95
H_2	2·70	KNO_3	0·09
		$(NH_4)_2CO_3$	1·78
		Charcoal	2·02

It is easy to understand that these gases and powders, while still white hot, may mix with a quick current of fresh air and dust, and start an ignition which stirs up the adjacent dust from the roof, sides and floor in large quantity and also stops the ventilating current momentarily. This stoppage will have the effect of shaking down dust from the walls and roof, between the point of ignition and the downcast shaft, out of the hitherto sheltered places in which it has been deposited.

As the result of the first ignition an inflammable mixture is again produced; this mixes with fresh air and coal-dust, and develops into an explosion of carbon monoxide and air. If the amount of dust in the air is sufficient, a dust explosion ensues.

CHAPTER IX.

COAL-DUST EXPLOSIONS. PART III. INFLUENCE OF THE MINE ATMOSPHERE.

INFLUENCE OF VENTILATION.

Pure dust and air explosions, in absence of fire-damp, are comparatively modern, but there is little doubt that in all large explosions dust has played an important *rôle*, even before the era of speeding-up of ventilation.

Most of the big dust explosions in recent years are to be attributed to increased ventilation. This has, it is true, very greatly reduced the number of small fire-damp explosions, but it has replaced them by dust explosions, fewer in number but of far greater magnitude. The recent Act of Parliament, generally referred to as a "Safety Bill," does not in reality make for increased safety when its provisions are carried out thoroughly. These provisions (in so far as the dust question is concerned) are, broadly, to prevent the dust from the screens entering the downcast shaft and to box in the coal more thoroughly on its way to the surface. These measures are in the right direction, but they are largely vitiated by the stipulation that every working place in the mine must contain not less than 19 per cent. of oxygen, and not more than $1\frac{1}{4}$ per cent. of carbon dioxide. In consequence of this limitation their effect will be to increase the danger zone (of dust explosions) so as to include places nearer to, or actually at the working faces.

If air containing 20·8 per cent., or thereabouts, of oxygen is carried to the working faces, dust explosions, at present unknown there (in spite of the enormous number of shots fired at the working faces), are likely to occur often. To keep dust out of the air and off the roads in a dry mine is out of the question. This will be readily understood when the enormous extent of the roadways is considered—many a mine has over ten miles of roads.

At first sight it seems extremely difficult to explain why a dust explosion travels against the ventilating current. It is true that it does sometimes travel with the air current, as well as against it, but this branch seldom develops violence. Anyone unaware of the phenomena would certainly expect the flame to be carried with the current of air rather than against it.

There is no doubt that against the air current, the flame or explosion products can mix more quickly and thoroughly with the air coming to it than with the air moving from it, and in the latter case the flame might be put out for want of oxygen. But this does not explain the fact that there is an explosive mixture of dust and air made on the intake side and seldom on the return, and that the explosion almost invariably travels towards the intake, although the air in the other direction has usually a little gas and so should require less dust to make an explosion.

What counts for most in an explosion is the fine dust already in the air. After this the chief part is played by the very fine dust deposited on the beams, props, sides and roof. Now in any airway with an appreciable current of air, this fine dust is deposited in the little ledges and cavities sheltered from the current by projections (a pronounced sheltering effect is caused by the props). In the flange of a girder, for example, the really fine dust is deposited not on the sides facing the current but on the reverse side. The side facing the current has very little dust on it and that little is of a coarser grain.

In the roads where the air current is very slow, the dust is deposited over all surfaces and sometimes more in the holes facing the current; in stagnant places the dust is deposited uniformly by the action of gravity.

There are millions of crevices on an intake road, in the walls, roof, props and floor, which are sheltered by projections of one kind or another and it is in these that the fine dust settles. An ignition of coal-dust by a blown-out shot or a fire-damp ignition (taking place, say on a haulage road in the first case, or at the face in the second case) stops the ventilating current suddenly on the intake side and then reverses it. The effect of this is to dislodge all the fine dust in the roads on the intake side and to put it into the air.

There is little tendency to dislodge the fine dust on the return side of the point of ignition, because, although the dust is there, the air current is in the same direction as before the ignition. Hence there is an explosive mixture formed on the intake but not on the return side.

The failure of the experimenters at Altofts to take into consideration these facts, concerning the mode of deposition and occurrence of dust in an actual mine roadway, caused their results to be very different from those that are observed in an actual coal-dust explosion in a mine. In many of their experiments the explosive violence was almost as great in the return as in the intake direction, which is *never* the case in a pure dust explosion in a mine roadway.

Possibly the phenomena observed during the recent disaster at Cadeby (July, 1912) may lead to a solution of the vexed problem as to why the explosion travels against the ventilating current rather than with it. In this disaster there were three explosions. The first went against the air-current; number two also travelled against the current, the usual ventilation having been continued for several hours between the times of the two explosions. After the second explosion the usual ventilation current was still maintained for some hours, but was perhaps somewhat impeded by a big fall in the intake. Stoppings were then built in the intake and return; the return one being finished first, stopped the current. Just as the intake stopping was being finished the third explosion took place. This was a feeble one compared with the others. There was no air current at the time, yet the explosion came out *in the same direction* as the first two and blew out part of the intake stopping; the stopping in the return was undamaged.

At the Home Office inquiry it was stated that at this colliery samples of air were taken regularly every day, in order to test the state of the mine, and some samples were taken during the interval between the first and second explosions, in the district in which these explosions occurred.

These samples showed that there was a little fire-damp present in the return. Why, then, did the explosions go towards the intake and not the return? Was it due to the draught, or did the lack of oxygen cause it to move towards the place where there was a bigger percentage, or had the first puff of the ignition put dust into the air in the intake and not in the return?

The fact that the third ignition and explosion came the same way as the other two, eliminates the draught factor, and the whole of the facts indicate that *the vital factor*, which causes the explosion in dust ignitions to travel towards the intake, is the formation of the explosive mixture of dust and air towards the intake, while in the direction of the return no such explosive mixture is formed, or only to a slight extent and for a short distance.

The Cadeby calamity has not solved the problem, but it has narrowed the issue sufficiently to make the solution easy by means of a few large scale experiments, well directed and properly carried out. Such experiments would certainly lead to increased safety; they might supply convincing proof of the value of some such mechanical device as is outlined in chapter IX., the reversal of the air-current at week-ends in order to remove the dangerous dust.

Influence of Fire-damp.

A close study of the minutes of evidence which the Royal Commission published in 1894 (not the report itself), from which numerous extracts have already been given, shows the division of opinion among mining people as to the part played by fire-damp. About one-half of the witnesses were certain that some dusts mixed with air alone could be ignited and cause an explosion. The others were equally certain that a mixture of coal-dust and air, in absence of fire-damp, could not be ignited and exploded.

Among the latter were many men who had spent years in mines, and it must be admitted that they had, apparently, very good grounds for thinking as they did. Moreover at the inquiry in 1880 into the cause of the disaster at Seaham Colliery, Sir Frederick Abel gave it as his opinion, that considering the number of shots fired and the few explosions that have occurred, there must be something else present besides coal-dust and air.

There was, in addition, the 1882 report (already mentioned) of MM. Mallard and Le Chatèlier (two of the most eminent chemists of the day, experts on explosions who had discovered the phenomenon of the explosive or detonation wave in gas mixtures), stating their opinion, after much experimental work, that no colliery explosion of any importance could be attributed with any probability to the action of coal-dust. The same views, or similar ones, had also been expressed in the final Report of the Royal Commission on Mines, published 1886.

On the other hand there are many records of explosions (*e.g.*, those at Altofts and Seaham) in districts where no gas could be detected explosions extending for miles where there was certainly no gas and very little dust. How then can these apparently contradictory sets of facts and opinions be reconciled? When the problem is studied in detail and a careful survey is made of all the records of explosions and of the experiments (numbering many thousands) carried out, some on the small scale, others in long galleries, in order to test the inflammability of dusts, one is struck by the complexity of the factors and the impossibility of interpreting the results in the light of any single theory.

The factors that influence the behaviour of dust are very numerous. They include:—

(1) The composition of the dust, and the length of time it has been exposed to air: in the same mine there are often many kinds of coal; different seams vary in quality and even in the same seam there are often different varieties, cannel and steam coal for example being found together.

(2) The fineness of the dust; the degree of fineness of any given dust may of course vary considerably.

(3) The purity of the dust; the coal-dust may be diluted with stone-dust and the quality and percentage amount of this is very variable.

(4) The composition of the air; the proportion of oxygen, carbon dioxide and fire-damp differs in different parts of the same mine.

(5) The means of ignition; an electric flash will ignite dust and air mixtures that a flame will not.

The variety of factors makes the problem very complicated, but it is essential that each should be considered. It is useless to consider the relative inflammability of coal-dusts unless the conditions are standardised. To say that any given dust is or is not inflammable is meaningless, until the degree of fineness of the dust, its past history and degree of purity, the composition of the air used and the means of ignition employed have been stated. Where discrepancies occurred among earlier results, it was usually through neglect of one or more of these factors. The importance of testing any given variety of dust with the air with which it is actually associated in the mine will be indicated later.

THE INFLUENCE OF THE PERCENTAGE OF OXYGEN IN DUST IGNITIONS.

Very many investigations have been made into the nature of coal-dusts, their composition and percentage of ash and volatile matter, the effect of diluting them with stone-dust, and the influence of these factors on the ignitability of the dust. But, curiously enough, the oxygen, which is at least equally important in inducing the explosion, has been left almost entirely out of consideration. It has not been overlooked altogether, but the part which oxygen plays in ordinary combustions, and especially in gas and dust explosions, has been far from fully appreciated by chemists and by others working on this subject.

The quotation which follows, taken from the "British Coal-dust Experiments,"* shows what was the attitude of the experimenters at the Altofts tube station towards the function of oxygen in explosions:—"The impossibility of preventing an explosion taking place by depriving it of the oxygen necessary to propagate combustion is so manifest that it need not be enlarged upon."

It is also strange that the rôle which coal-dust itself plays in an explosion has been assumed (without any facts in justification) to be that of a gas like hydrogen.

A close study of the evidence of witnesses before the Royal Commission, which published its report in 1894, and of other Government Blue Book records of explosions, reveals the fact that the mines in which dust explosions occurred were invariably well-ventilated and that the explosions took place in the best ventilated parts, the working faces and the return ways being usually unaffected. In the absence of gas, a dust explosion has never been known to originate at the working face. It is quite true that many working faces are damp and dustless, but there are many that are dry and dusty, and by several investigators* the dust there has been found to be more inflammable than that in the haulage roads.

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* *Record of First Series of British Coal-dust Experiments*, 1910, page 106.

In this country alone more than fifty million shots are fired in mines each year and nearly all of these at the workings, yet not a single dust explosion is known to have originated at the workings. On the other hand, comparatively few shots are fired in the intake haulage ways, yet most of the dust explosions have originated in them.

The amount of air passed through a modern mine is enormous; 200,000 cubic feet per minute is quite common, and in some large mines it reaches 500,000 cubic feet per minute. The primary reasons for this are, first, to ensure that no accumulations of fire-damp occur and, secondly, in the case of deep mines, to maintain the temperature at a reasonable figure for the health and comfort of the men. But frequently the quantity of air passed through is far greater than is necessary to effect these purposes.

The changes that occur in the composition of the air on its way through the mine are quite appreciable: the percentage of oxygen is gradually reduced while that of carbon dioxide is slightly increased. Coal absorbs oxygen and the fresh coal on the tubs takes it up rapidly, but the chief factor in causing the change in composition is the black-damp, which is constantly given off by the waste in most mines.

At the working faces the fresh coal absorbs oxygen rapidly, and also gives off black-damp (and often fire-damp too), so that here the percentage of oxygen is always less than in normal air. Often it is reduced below 20 per cent., sometimes below 19 per cent., while as little as 17 per cent. is occasionally found in places where, for any reason, the ventilation is difficult.

In Whalley's investigations on the air of average mines

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* Bedson, *T. I. M. E.*, vol. xxxix., part 5.

(not selected cases) in Scotland,* it was found that 20 returns out of 52 examined and 7 working faces, out of 18, contained less than 19 per cent. of oxygen and more than 0·5 per cent. of carbon dioxide in the air.

In Prof. Cadman's examination of the air of 43 collieries in England† it was found that out of 113 samples taken at the working faces there were 23 which contained 20·5 per cent. or more of oxygen, 43 with 20-20·5 per cent., and 47 in which the oxygen was below 20 per cent.

Even when the air in the main return shows a high percentage of oxygen, it must not be concluded that the air at the working faces is of equal quality; near the working faces there is a considerable amount of leakage from intake to return ways, *i.e.*, the air "short circuits," and, moreover, the workings in pits are the most difficult parts to ventilate as they are constantly being moved forward.

A Method of Preventing Explosions.

Putting the above evidence side by side with the phenomena, given in chapter II., that relate to the influence of the percentage amount of oxygen present on combustion, it will be seen that we have three distinct sets of facts bearing on the possibility of explosions, viz.:—

(1) Dust ignitions are unknown at the working faces and, in the absence of gas, seldom, if ever, traverse the workings and returns.

(2) The air at the working faces always contains less oxygen and more carbon dioxide than normal air; very often the oxygen is reduced below 20 per cent., and in many cases below 19 per cent., while as much as 0·5 to 1 per cent. of carbon dioxide is sometimes present.

(3) Methane will not burn in air that contains less than 17½ per cent. oxygen, and the flames of oils

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* Blue book, Cd. 4551. † Loc. cit.

> and waxes, and even of such inflammable substances as petroleum ether, go out while there is still a large amount of oxygen in the air.

Considering these sets of facts simultaneously, the author formed the hypothesis that they were closely connected, the reason why dust ignitions did not occur at the working faces and returns being that the air in these parts contained less oxygen.

To test this hypothesis the simple apparatus shown on page 107 was used. It consists of a glass tube A, 14 inches long, 2 inches inside diameter, with side tubes EE′ through which platinum terminals are inserted with their ends about half an inch apart.

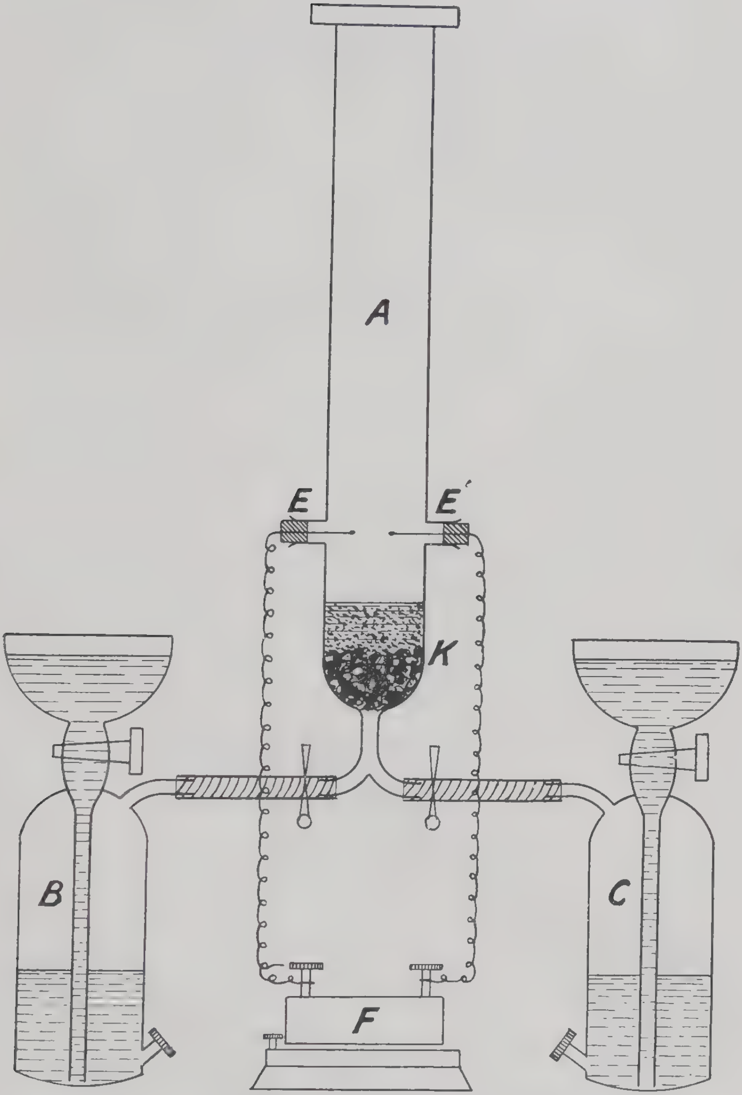
The tube A is drawn out at the bottom and is provided with a Y tube one branch of which is connected with a gas holder containing ordinary air and the other with a similar one containing prepared air that usually had less oxygen and more carbon dioxide than normal air.

A battery (not shown in the figure) was used to supply current to the coil F.

A few small pieces of coke are placed in the tube at K to prevent the small tubes at the bottom being clogged up by dust. These also serve to divide up the stream of air from the gas-holder.

The dust to be tested is put in the tube A, on top of the pieces of coke, several puffs of air from the gas-holder containing the prepared mixture are then given and a discharge from the powerful coil is, at the same time, passed between the platinum terminals.

On testing various dusts in this way it was found that even the dusts which were most inflammable in ordinary air would not ignite (with exactly the same discharge of sparks) when mixed with air containing 19 per cent. of oxygen and 0·75 per cent. carbon dioxide. Indeed a reduction of the oxygen to 20 per cent. with 0·5 per cent. carbon dioxide present was sufficient to prevent ignition of most mine dusts.



Apparatus for Testing the Degree of Inflammability of Coal-dusts in use in the Chemical Laboratories at Liverpool University.

In order to determine the amount of reduction of oxygen and the quantity of carbon dioxide necessary to prevent ignition of any particular dust, air containing about 18 per cent. oxygen, 1·5 per cent. carbon dioxide and 80·5 per cent. nitrogen was first tried, to make sure that it did not ignite. Then some ordinary air was admitted to the gas-holder, and the new mixture tried again, and so on until the sample of dust just showed signs of ignition. At this point a sample of the air mixture was taken without delay and analysed for its contents of oxygen and carbon dioxide.

From time to time normal air from the other gas-holder was tried with the same dust to ascertain that the spark was strong enough and the dust fine enough and in sufficient quantity for ignition.

For testing mine dusts to see if they are inflammable with ordinary air only one gas-holder is required, of course, and if the tests are to be made near the colliery, the gas-holder can be replaced by a large bellows fitted with a valve on the outlet, and the actual air in the mine (from the place where the sample of dust was taken) can be used. Some of the results obtained with the apparatus described on page 107 are shown in the accompanying table.

In the case of some mine dusts the presence of even a small proportion of stone-dust seems to be sufficient to render the dust non-inflammable. With other dusts, on the contrary, a large proportion of stone-dust appears to have little effect. Seams that supply coal-dust which is very inflammable when made in the laboratory (from fresh coal) may produce, in actual practice, a dust that is comparatively safe in one mine and dangerous in another that is working the same seam. This is probably due to differences in the composition, proportion of admixed shale-dust, and degree of fineness caused by different methods of working the mines.

The only *pure* coal-dust hitherto examined which does not give an ignition with normal air in the above apparatus is some South Wales anthracite. It is significant that in the

TABLE SHOWING THE DEGREE OF IGNITION OF DIFFERENT COAL-DUSTS WITH VARIOUS ATMOSPHERES.

Dusts.	Percentage of Ash.	Normal Air.	Air: 19·3 per cent. of Oxygen and 0·65 per cent. of Carbon Dioxide.	Air: 19·2 per cent of Oxygen and 0·9 per cent. of Carbon Dioxide.	Air: 18·0 per cent. of Oxygen and 1·5 per cent. of Carbon Dioxide.
Barnsley Seam—					
Pure coal-dust—(1*)	1·3	Full.	Just full.	Partial.	—
Do. do. (2*)	—	do.	do.	do.	—
Do. do. (3*)	—	do.	do.	do.	—
Screen-dust ...	10·4	None.	—	—	—
Dust from timber in haulage-ways—(*a*)	19·5	do.	—	—	—
Do. do. (*b*)	33·0	do.	—	—	—
Lancashire Coal—					
Arley Coal* ...	—	Full.	Full.	Full.	None.
Three-Quarters Coal*	—	do.	do.	Nearly full.	do.
Plodder Mine* ...	—	do.	Just full.	Partial.	do.
Yard Coal*	—	do.	do.	do.	do.
Arley Mine dusts (*a*)	7·7	None.	None.	—	—
Do. do. (*b*)	17·1	do.	do.	—	—
Do. do. (*c*)	25·9	do.	do.	—	—
Three-Quarters Mine dusts ... (*a*)	50·0	Full.	do.	—	—
Do. do. (*b*)	36·0	None.	do.	—	—
Do. do. (*c*)	37·0	Partial.	do.	—	—
Do. do. (*d*)	33·4	do.	do.	—	—
Plodder Mine dusts (*a*)	14·8	Full.	do.	—	—
Do. do. (*b*)	22·5	do.	do.	—	—
Yard Mine (*a*)	23·1	do.	do.	—	—
Do. (*b*)	24·5	do.	do.	—	—
Wigan—					
Arley Mine dusts (*a*)	—	do.	do.	—	—
Do. do. (*b*)	—	do.	do.	—	—
Blackburn—					
Mountain Mine Coal*	—	Full.	do.	—	—
Mine-dust	11	None.	—	—	—
Screen-dust ...	—	do.	—	—	—
South Wales—					
Ferndale Coal*† ...	—	None.	—	—	—
Mine-dust ...	—	do.	—		—

* These dusts were made in the laboratory from samples of fresh coal.

† Anthracite.

Altofts tube experiments it was found impossible to get an ignition, against the air current, with anthracite dust from South Wales.

A very important point, whch must not be overlooked in the case of dusts taken from the mine, is that they have had the most inflammable portion removed by the ventilating current. Because a mine-dust will not ignite in the above apparatus, it does not follow that it must consequently be safe in the mine itself. In the test apparatus it is mixed with pure air, whereas in the mine it would be associated with air containing in suspension a certain quantity of very fine and highly inflammable dust, together possibly with inflammable gas and vapour.

The dust which can be seen floating in the air in some mines is so fine that it is extremely difficult to collect it; it will pass even through fine swansdown calico.

For the test to be really practical, the dust sample must therefore be tried with a sample of air from the same place in the mine; if this is not possible a suitable margin must be allowed when clean normal air is used. It was probably neglect of *this point of vital importance* that caused the Austrian Fire-damp Commission to declare safe the Camphausen dust that shortly afterwards gave such a serious explosion. Possibly, too, this may explain why in some of Sir H. Hall's experiments no ignition was obtained with several dusts which subsequently, in the pits themselves, gave disastrous explosions.

A set of experiments that illustrates this point rather well was carried out with mine dusts from a colliery working a certain seam, which is known to be rather fiery and dangerous. Screen dust, dust from the intake haulage ways and dust made artificially from the coal were examined in the above apparatus. It was found that none of these except the artificially made dust would ignite with ordinary air; the artificially made dust ignited every time and quite readily.

On analysis it was found that the ash contents varied in the following manner:—

Screen dust	10·4 per cent. of ash.
Dust from timbers in intake (1)	33·9 ,, ,,
,, ,, ,, (2)	19·5 ,, ,,
Dust made artificially	1·3 ,, ,,

It is of interest to note that although the screen dust would not ignite with ordinary air, it readily gave an ignition when the amount of oxygen had been increased to 23 per cent.

A quantity of the same screen dust was taken and a separation made by blowing a gentle current of air through it and collecting the fine dust (air floated) which was carried away. This fine air-floated dust easily ignited in ordinary air although the original screen dust, with the same source of ignition and the same air, would not.

Now if the light portion, separated in this manner from the screen dust, is so inflammable, it is evident that the dust which has already been separated from it in the mine itself, by the ventilating current, must be still more dangerous. For it is this very fine dust that plays the most important part in the propagation of a dust explosion.

It must always be borne in mind that what counts for most, in the propagation of a dust explosion, is the presence of very fine dust, which is either already in the air or is put into the air from the roof, sides and floor by a momentary stoppage of the ventilating current. When the ignition has once attained sufficient speed and violence the explosion will be propagated by very little dust.

INFLUENCE OF CARBON DIOXIDE.

In the course of the experiments with reduced amounts of oxygen, it was noticed that the restraining influence of a little carbon dioxide was considerably greater than that of an equal quantity of nitrogen. In many instances it was observed that a dust which would not ignite in the evening, with the gas in the holder, would ignite with it next morning. This was found to be due to the removal of the small quantity of carbon dioxide by the solvent action of the water during the night. In one series of experiments, made in order to test this point, it was found that a mixture containing 19·25 per cent. oxygen, 80 per cent. nitrogen and 0·75 per cent. carbon dioxide behaved, as far as ignition of dust was concerned, just like one containing 17·5 per cent. oxygen and 82·5 per cent. nitrogen.

These results indicate one of the reasons why most of the dust explosions that have occurred in intake haulage ways have been stopped before they reached the workings. They died out on account of the smaller percentage of oxygen in the air there and the presence of an appreciable amount of carbon dioxide (see also page 100).

The Iowa Mine Explosions, 1892-1903.

In the light of the preceding hypothesis as to the dependence of dust explosions on the oxygen contents of the air, it is very instructive to consider the phenomena of the Iowa explosions in 1892-1903. These were recently described by Mr. J. Verner in the *Coal Age*.* The Iowa Mines are mostly dry and dusty, a large quantity of powder is used, amounting, in the larger mines, to as much as a ton per day. For several reasons the elaborate ventilation employed in many mines in the Eastern States cannot be used in Iowa. The ventilation (now improved) was in former years unsatisfactory in many instances. This was partly due to bad management, but was also, to some extent, a result of the entire absence of fire-damp.

Wheatsheaf No. 1 mine was opened out in Lucas county in 1876; No. 2 mine in 1880. Both of these mines were dry and dusty. No. 2 was opened out by experienced men, much pick-work was done and little powder used. The miners were accustomed to light their own shots, one at a time, at the end of the shift. This system was continued for some years until the men who were doing narrow work found that, by drilling holes two or three feet ahead of the cut, they could extract more coal with less labour. Consequently they adopted this new system, and to escape the unpleasant and dangerous task of going back through the powder smoke, they resorted to the fuse.

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* "The Causes of Explosions in the Iowa Mines," *Coal Age*, Feb. 3, 1912.

Meanwhile, these mines had become very extensive, with the workings a considerable distance from the shaft. The air-ways were much obstructed by falls, the presence of black-damp was noticeable, especially in the returns, and the ventilation was unsatisfactory. There was so much dust that great clouds of it were raised by men and mules travelling the haulage roads. These conditions existed for years, until the mines were worked out and abandoned. Hundreds of shots, tamped with dry coal-dust, were fired every day and about 5 per cent. of these blew out while another 10 per cent. or thereabouts were ineffective. Yet no explosion occurred.

No. 3 White Breast Pit was then opened. This mine was well ventilated and had only a little dust, but an explosion occurred, although the system of working was quite similar to that which had been used with impunity for years in No. 1 and No. 2 pits. The variety of coal was the same in all three pits.

In 1900, the White Breast Pit No. 4 was opened. It was dry and had some dust, but more supervision was exercised over the shot-firing: prepared shots were inspected by examiners and those accepted were fired after the miners had left. In this pit a violent explosion occurred in 1901, killing the shot firers. A month later a second and more destructive explosion occurred, and in January, 1902, a third wrecked part of the mine and killed the shot-firers.

After each of these explosions Mr. Verner inspected the mine and reported that the first and third explosions were caused by improperly prepared and overcharged shots. In the case of the second explosion, the two shots fired in the place where the explosion occurred were not overcharged and did the work fairly well. He added that all these explosions were propagated and extended by dust.

No change was made in the methods of working, but there was the expectation, based upon experience gained at the mines, that increased extension of the mine would diminish the risk of explosion. This expectation was justified in that no further explosion occurred during the next six years. The mine remained dry and dusty, becoming even dustier, and there was no perceptible decrease in the number of blown-out shots.

The Pekay mine was opened in 1891 by men who brought with them the practice of blasting which they had used with impunity for five years in other mines in the district. In this new and well-ventilated mine a violent explosion occurred while the workings were only a few hundred feet from the shaft. The disaster made the men more careful in placing their shots, but no radical change was made in the methods.

In 1899 Mr. Verner examined this mine and found the ventilation had become very unsatisfactory; the airways were obstructed by falls and the amount of dust had increased as the mine extended. The miners had evidently decided that no further explosion need be feared, for the shots were tamped with dry coal-dust and were very rapidly fired, by fuse, at the end of the shift. As many as five holes, tamped loosely with dry dust, were fired simultaneously in one place, yet there was not the least sign of any ignition of dust. Moreover, blown-out shots were of daily occurrence. The mine was worked under these conditions until it became exhausted ten years after the date of the explosion.

Apparently the mines in which no explosions occurred differed from the others only in their inferior ventilation and in their greater extension, the working places being further from the shaft, and the airways longer and less open.

Mr. Verner's explanation was that the difference in behaviour was due primarily to differences in the degree of draught. Now a draught may have some influence in inducing an ignition of dust, but it requires a very considerable increase in the draught to have even a small effect on the ignition, whereas the author's experimental work has conclusively proved that ignition is profoundly affected by a very slight change in the proportions of oxygen and carbon dioxide.

Black-damp was frequently noticed in the Iowa mines and the presence of this, together with the insufficient ventilation and the absorption of oxygen by coal, as the air made its way through the longer workings in the older mines, might easily have resulted in the oxygen contents being reduced to 19 per cent. or thereabouts. In such an atmosphere, especially with a little carbon dioxide, the dust would not ignite.

In the newer mines the air had to pass only through a few hundred feet of roadway and had not time to lose much oxygen, at any rate not enough to prevent disaster from the reckless shot-firing which Mr. Verner describes. It is much to be regretted that no record was given of the analyses of the air in these mines, if such analyses were ever made. Yet, even in absence of them, the phenomena described point unmistakably to the correctness of the view that the deciding factor was the composition of the air: that the dustiest mines are safe when there is a little carbon dioxide present and the amount of oxygen is reduced sufficiently.

Evidence similar to that which is recorded of the Iowa mines exists in the case of many other mine explosions, but the above summary is sufficient to indicate its nature and the importance of its bearing on the question of ventilation and the composition of the atmosphere in mines.

Opinions of Sir H. Hall and Mr. J. Gerrard.

In concluding this survey of our knowledge of coal-dust explosions, the following expressions of opinion from two leading authorities are apposite:—

Dealing with the causes of coal-dust explosions, Sir Hy. Hall* stated that he had watched explosions carried out experimentally on a considerable scale, and his impressions, confirmed by the results of many other investigations, were that the possibility of dust explosions depended mainly on three conditions:—

(1) The coal-dust must be in the air at the start: so long as it was on the ground it was as innocuous as soil or any other substance.

(2) It must be of such a nature that it readily gives off its volatile matter: the more readily it yields up its volatile gases and the lower the temperature at which it loses them, the more dangerous the dust.

(3) The dust must, at the beginning, be in such a position that the ignition sets up a certain amount of pressure.

As to the method of preventing dust explosions, and the uncertainty that still exists, Mr. John Gerrard* in a dis-discussion on explosions is reported to have said:—"The danger in connection with coal-dust is not the excess of coal-dust, but rather the exceedingly small amount that is necessary to initiate an explosion. All I have heard from practical mining men, from men working in the mines, pointed to their want of appreciation of the small amount of coal-dust that is necessary to initiate an explosion. And, secondly, the very small amount of flame that is required to cause that result. For years we have had it impressed upon us that one could only get a coal-dust explosion by a violent blown-out shot. We have had explosion after explosion initiated without any trace of a blown-out shot. . . . . . . We have discussed the question as to whether preventive zones might meet the case; but those who have seen the terrible force of the explosions at Altofts must recognise that, once an explosion of coal-dust was initiated, the terrific force must involve a considerable loss of life before the preventive zone was reached. *I have absolutely abandoned all hope of preventing loss of life by limiting zones. Coal-dust explosions must be nipped in the bud.*"

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* *T. I. M. E.*, vol. xxxix., part 5.

CHAPTER X.

PREVENTION OF EXPLOSIONS.

Apart from the ordinary precautions in use at present, precautions which, as is well known, prove inadequate at times, there are four distinct methods of preventing explosions in mines. These methods are—

(1) Removing the dust from the intake haulage ways by periodically reversing the ventilation.
(2) Reducing the percentage of oxygen in the ventilating current (as outlined in chapter IX.).
(3) Watering the floor, roof and sides of the roadways.
(4) Rendering the coal-dust non-ignitable by mixing it or covering it with stone-dust.

Method 1.—Removal of the Dust.

The method of removing dust from the intake haulage ways by reversing the current, when the men are out of the pit (*e.g.*, at week-ends), is one devised by the author (in the first instance for diminishing the frequency of gob-fires), and was first put forward at a meeting of the Manchester Geological Society* in October, 1912. There is no doubt that a reversal of the ventilating current removes a very large quantity of dust from the pit, and if it were reversed several times during the week-end all the really dangerous dust would be removed; this procedure could advantageously be followed up by stone-dusting on Monday morning.

When one examines the deposits of dust in a mine, it is found that, in an airway with any appreciable current of air, all the fine dust occurs on the roof, sides and floor in the innumerable holes, crevices, etc., which are *sheltered* from the prevailing air current (see page 98). On stopping and reversing the ventilating current, this dust is no longer sheltered, but, on the contrary, is exposed to the full breeze and is thrown at once into the air and carried along by the current.

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* "Gob-fires and the Prevention of Gob-fires in Mines," *Trans. Inst. M. E.*, vol. xliv., part 2.

Each reversal throws dust into the air. The best method of removing this dust is to reverse the current only for a minute or so, and then resume normal ventilation for a few minutes (10 minutes or thereabouts, according to the speed of the air and the length of the roads), then reverse again for a minute and follow this by normal ventilation for a few minutes, and so on until it is seen that no more dust is raised.

There is no reason why the current should not be reversed for a few minutes each night as well, but it cannot be too strongly insisted upon that there should be *no lights* (safety-lamps or electric lights) *burning in the pit in the returns*, as the presence of dust in the air is a source of great danger. Even non-inflammable dust, in the presence of 2 per cent. of gas in the returns, may produce a dangerous mixture ignitable by a defective safety-lamp or an electric spark. Therefore no lights should be permitted in the returns containing gas during the reversal of the ventilation, and, moreover, all electric current should be shut off from the pit as an extra precaution.

There is no doubt that dust that cannot be removed by reversal of the ventilation, as described, cannot be put into the air by an ignition of fire-damp or a blown-out shot, and such reversal, done thoroughly in the manner described, is the simplest method yet proposed of rendering a pit safe from dust explosions.

Under the 1911 Act (the Safety Act), all mines must be provided with means for reversing the ventilating current. This regulation was passed with the idea that a reversal of the ventilation would be a valuable means of extinguishing a fire in the roadways of a mine; this is no doubt correct and a useful procedure in the case of *damp* mines. But it is as well to emphasize here that reversal of the ventilation in a dry and dusty mine, with a fire in the roads, is like applying a barrel of gunpowder to a lighted match: there is little if any doubt that, in nine cases out of ten, a huge dust explosion would be the immediate result of any such procedure.

This is one of those faulty provisions with which this Act abounds, but, unlike the others, it may prove to be a blessing in disguise since, after making this compulsory alteration, managers will have immediate means at their disposal for removing dust and for reducing the number of gob-fires.

METHOD 2.—REDUCTION OF THE OXYGEN.

The conditions required in this method are attained naturally in some mines near the working faces and in the returns, by reason of the absorption of oxygen by the coal, as already described.

The reduction of the percentage of oxygen in the ventilating current is undoubtedly the surest method of rendering mines safe from both gas explosions and dust explosions, as well as from the more frequent though less sensational *fires in the roadways.*[*] This method, founded on the author's work and only recently discovered, is not yet in practice, though it has been proved that it can be worked on the large scale with every satisfaction. It is based on a lengthy investigation of the combustible properties of different mixtures of dust and air, and of methane and air (both with and without the presence of carbon dioxide) with various percentages of oxygen, and under the actual conditions that hold in mines, as nearly as these can be reproduced in the laboratory.

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[*] During 1911 there were 167 ignitions of fire-damp or dust and 132 underground fires recorded in the coal mines of Great Britain.

The limits of inflammability of fire-damp with ordinary air are about* 5½-13 per cent. of methane, *i.e.*, if the air contains less than about 5½ per cent. or more than 13 per cent. methane it will not ignite. These figures are not yet as precisely determined as is desirable; varying values have been given by different observers, especially for the lower limit, and this is undoubtedly because they have worked under different conditions. Thus Abel says that air containing 4 per cent. of the gas from a Garswood Hall colliery blower was explosive, but this gas was found to contain some ethylene.

Quite recently a very fine research in the pure science of the subject has been carried out by Burgess and Wheeler, but unfortunately their figures are of little value to practical mining people, as the means of ignition employed—a spark from an induction coil—is in no way parallel or similar to the conditions which may and do cause fire-damp ignitions. No careful worker in a mine will fire shots when gas can be detected in the neighbourhood. The usual causes of ignition of gas in a mine are a small flame, a match, an open candle light or a defective safety lamp. Therefore in estimating the limits of ignition a small flame, about the size of that used in a safety lamp, should be applied to the gas mixture.

Haldane and Atkinson† state that fire-damp and air mixtures, containing as little as 12 per cent. of oxygen, could be exploded, and Dr. J. S. Haldane recalls this work‡ and points out that these mixtures were made with fire-damp from a mine and were ignited by an ordinary candle flame. This statement is, of course, absurd, as a candle flame will not burn in air containing less than 17 per cent. oxygen; how then could it be used to explode a mixture of gases containing only 12 per cent. oxygen! What they probably did was to light the mixture *in air*, so that the mixture burnt *in air*, which is, of course, very different from the gas mixture burning *per se*.

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* See page 26.

† *T. I. M. E.*, 1895, vol. viii., p. 549.

‡ *T. I. M. E.*, vol. xliii., p. 271.

A mixture of 31 per cent. methane, 12 per cent. oxygen and 57 per cent. nitrogen would, of course, burn in air; and on diluting one part of such a mixture with 2½ parts of ordinary air an explosive mixture *per se* would be formed.

The author has found that some mixtures of marsh gas (freed from hydrogen) with air containing a reduced percentage of oxygen behave as follows:—

16 parts oxygen 84 ,, nitrogen 8 ,, methane	No ignition with a small coal gas flame.
17 parts oxygen 83 ,, nitrogen 8½ ,, methane	No ignition with a small coal gas flame.
17½ parts oxygen 82½ ,, nitrogen 8¾ ,, methane	No ignition with the tube horizontal or mouth up; ignition with the mouth downwards.[*]

These experiments, which are being continued, indicate that when the air contains 17½ per cent. oxygen the higher and lower limits coincide, and with exactly the theoretical amount of methane necessary for complete combustion, an ignition is possible. The chance of getting such a mixture in practice in a mine with a 17½ per cent. oxygen atmosphere is so remote that it need not be considered.

Since, with ordinary air, the explosive limits are about 5½ per cent.-13 per cent., while with air that contains less oxygen both limits are drawn in until they coincide at

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[*] The generally accepted fact that mixtures of air and fire-damp containing 13 per cent. (and over) of marsh gas are not explosive confirms the author's results, as such a mixture contains over 18 per cent. of oxygen.

$8\frac{3}{4}$ parts (or thereabouts) of methane per 100 of air, when the air contains $17\frac{1}{2}$ per cent. of oxygen, it is evident that the chance of ignition with air that contains, say, 19 per cent. oxygen mixed with marsh gas is enormously less than with ordinary air that contains 21 per cent. oxygen.

The above figures apply to clear gases. They may not hold for gas that contains *dust* in suspension. There is no lack of evidence that gaseous mixtures, which are not inflammable when dust-free, may be ignited in the presence of certain kinds of dust—which dust may itself be non-inflammable and yet produce this effect. Sir F. Abel considered that the action of certain porous bodies in the form of dust is to bring the molecules of the gases into closer contact, and thus promote chemical action and the development of heat, whereby the gaseous mixture is raised eventually to the temperature of ignition. This action is not too well understood, even in modern times, but there is no doubt that certain solid catalytic substances lower the temperature required for ignition.

Most if not all kinds of coal are powerful catalysts in bringing about the combination of inflammable gas and oxygen. Reasoning from analogy, it is not impossible, however, that some dusts may have the opposite effect and retard combination.

A reduced oxygen atmosphere is readily produced by mixing ordinary air with the calculated amount of nitrogen and carbon dioxide, which mixture is easily obtained by the combustion of suitable fuel, but great care must be taken that it contains no carbon monoxide. The exhaust gas from an ordinary Otto cycle or other gas engine, with its exhaust apparatus suitably modified, will give excellent results, if the air supply is controlled and complete combustion attained. This can be done by leading the hot gases over a catalytic surface.

Since reading the paper previously mentioned, the author has had the opportunity of working out on the large scale the production of inert gas free from carbon monoxide. Using a 25 H.P. gas engine, the exhaust gas was found to be so hot (1,100° F.) that complete combustion was readily effected without the use of a strong catalyst. All that was necessary was to pass the hot gases, directly after leaving the cylinder, over ordinary broken firebrick, which offers plenty of surface.

But in many cases it would not be convenient to use such a source, and the products of combustion from a gas-fired or coal-dust fired boiler would be preferred. The exhaust gases from these would certainly not be so hot as 1,100° F., but, by the equilibriating device described below, complete combustion can be induced, without any excess of oxygen, carbon monoxide or other unburnt material being left in the gas. This device can also be used with the gases from an ordinary Lancashire boiler, the gas being passed through the apparatus before the economiser is reached.

The equilibriating apparatus (called an *Equilibriator*) consists of an iron vessel divided into two parts; the front part is packed with $\frac{1}{2}$-1 inch pieces of special bricks made of a mixture of clay and titaniferous bog iron ore, or any other suitable catalyst, while the second part is packed with granulated copper or scrap copper wire. The bog iron ore bricks have the property of causing combustible gas and oxygen to react at a low temperature, and by this means the last traces of gas are oxidised to carbon dioxide and water.

If there is an excess of gas it is removed by the copper oxide, while if there is an excess of oxygen it is removed by the copper that is simultaneously present. To oxidise some of the copper a slight excess of air is introduced when the apparatus is started, but in normal working, when sufficient copper oxide has been once formed, only the exact amount of air required for complete combustion is allowed.

Owing to fluctuations of pressure and other conditions, there will at one time be a slight excess of air and at another a slight excess of gas. The presence of both copper and copper oxide neutralises both these effects. Silica plates can be fitted into the copper packed part of the apparatus, so that any prolonged reducing or oxidising action can be seen and remedied by regulation of the air supplied to the engine or boiler.

By means of this apparatus a constant supply of inert gas, of known composition and entirely free from carbon monoxide, is automatically obtained. It has been found that bog iron ore will induce the combination of carbon monoxide and air at a little below 390° F.; and at temperatures above this it acts rapidly and completely. This catalyst will bring about the combustion of hydrogen at 212° F. and possibly below that temperature. The author has used it instead of palladium in the estimation of hydrogen in gas mixtures.

Whatever the source of the burnt gases, they may, after treatment in the manner described above, be cooled and used directly, but it is preferable to remove any sulphur dioxide if present. This is easily done by passing the gas through a scrubber charged with limestone. If a gas engine is used, it is perhaps better to take out the sulphur compounds before the gas reaches the engine.

The inert gas treated in the manner that has been described consists of 81-81½ per cent. nitrogen and 19-18½ per cent. carbon dioxide. After passing the equilibriator and limestone scrubber or tower, the gas can be exhausted directly into the downcast shaft, in the right proportion to make an explosion impossible. But a good way of applying the gas to the mine ventilating current is to compress it in an ordinary air compressor and use it as motive power in air engines that are doing haulage work. It can be so arranged that all the water (and with it some considerable quantity of carbon dioxide) is removed by drain traps.

The proportion of inert gas required in any particular place depends, of course, upon the nature of the seam. It can quickly be estimated after an examination of the dust and the mine gases. But it cannot be too strongly urged that this method would enable owners to render their mines perfectly safe from explosions and fires. At present it is a matter of chance in many mines whether explosions occur or not: managers work in constant trepidation and count themselves lucky if, by means of great precautions and constant watchfulness, explosions are avoided. Whereas, by scientific control and modification of the air supply, every factor of chance can be eliminated and the safety of the mine made a matter of certitude.

The relative rarity of coal-dust explosions in itself points to the fact that ordinary air, with its 20·9 per cent. of oxygen, is near the border—the lower oxygen limit necessary for the ignition of even pure coal-dusts. In fact it is below the limit for some South Wales anthracites. A very slight reduction, say to 20 per cent., with ½ per cent. of carbon dioxide present, will make the intake haulage ways of the average mine quite secure against dust explosions. As the chance of gas in the intakes is practically *nil*, they would then be safe from both dust and gas explosions.

With the more dangerous kinds of dust a reduction to 20 per cent. of oxygen with ½ per cent. carbon dioxide present, would not be a sufficient precaution; the reduction must be to 19 per cent. oxygen, or less, with ¾-1 per cent. of carbon dioxide present. A reduction of oxygen by the small amounts mentioned above would not entirely remove the possibility of fire-damp ignitions but it would very greatly diminish the chance of accidents, and by further reduction to the limit found experimentally, *i.e.*, 17½ per cent. oxygen, the risk of explosions could be entirely eliminated.

OPINIONS OF SOME AUTHORITIES.

The problem of colliery explosions was referred to by *Dr. Leonard Hill*, F.R.S., in his Presidential Address to the Physiological section of the British Association, 1912.

His general topic was that sunlight and moderate temperature were more important to human health and vigour than artificial ventilation on the usual lines, which aimed at attaining a very low percentage of carbon dioxide.

In condemning the high standard of oxygen demanded by law in coal mines, he said "the simplest method of preventing explosions in coal mines is that proposed by Dr. J. Harger, viz., to ventilate them with air containing 17 per cent. of oxygen. There is little doubt that all the great mine explosions have been caused by the enforcement of a high degree of chemical purity of the air. In the old days, when ventilation was bad, there were no great dust explosions. Mr. W. H. Chambers, general manager of the Cadeby mine, where the recent disastrous explosion occurred, with the authority of his great and long practical experience of fiery mines, told me that the spontaneous combustion of coal and the danger of explosion can be wholly met by adequate diminution in ventilation. The fires can be choked out while the miners can still breathe and work. The Coal Mines Regulation Acts enforce that a place shall not be in a fit state for working or passing therein if the air contains either less than 19 per cent. of oxygen or more than 1¼ per cent. of carbon dioxide. . . . The regulations impel the provision of such a ventilation current that the percentage of oxygen is sufficient for the spread of dust explosions along the intake airways, with the disastrous results so frequently recorded. If the mine were ventilated with air containing 17 per cent. of oxygen, in sufficient volume to keep the miners cool and fresh, not only would explosions be prevented, but the mines could be safely worked and illuminated with electricity and miners' nystagmus prevented."

Writing privately, Dr. Leonard Hill adds that he cannot see any objection to the ventilation of mines with air containing 17½ per cent. oxygen so long as this air is free from poisonous impurities, such as carbon monoxide, and is introduced in sufficient volume to keep the atmosphere at the working faces cool and moving.

The good health and vigour of the miner depend greatly on the coolness and movement of the air. He can work in such air without ever straining his heat-regulating mechanism, and such air, by its cooling property, promotes his appetite and his bodily and nervous health.

Dr. Leonard Hill also refers* to the "most interesting statements made by Dr. Harger concerning the burning of acetylene in 12 per cent. of oxygen. The acetylene lamp gives a ready means of protecting the miner from air that was too much deoxygenated. Dr. Harger's plan would abolish the use of safety-lamps, allow proper lighting of the mine, abolish miners' nystagmus, and make the use of electrical apparatus (for haulage, etc.) quite safe. There are consequently many points in its favour."

Dr. J. S. Haldane, F.R.S., in a letter to the author, says: "I can see no physiological difficulty in reducing the oxygen to 17½ per cent., provided that you can get over the difficulties with carbon monoxide and ensure proper purification of the furnace gases from carbon dioxide, etc., and can also overcome the lighting difficulties.

"The oxygen standard of the Mines Commission was aimed chiefly at ensuring proper light and sufficient air to get rid of accidental impurities from the use of explosives, etc. As regards carbon monoxide, it would be necessary to ensure less than ·01 per cent. in the mine air, *i.e.*, in the mixture of furnace gas and pure air."

Professor Benjamin Moore, F.R.S., states that a reduction of oxygen to 17-18 per cent. will make no difference to the miners' health, and that a small amount of carbon dioxide (*e.g.*, 1 per cent.) is certainly not injurious.

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* *T. I. M. E.*, vol. xliii., part 3, p. 285.

METHOD 3.—WATERING.

Watering the roadways, floor, roof and sides, a method first advocated by W. Galloway, is in very general use in Germany, where it is compulsory; there are thousands of miles of water mains in the mines in the Westphalia district. It is also in use to some extent in mines in South Wales.

Where it is carried out thoroughly, this method is no doubt effective, but it must be understood that merely putting water on the floor of the roadways from time to time is of no use, and in fact may be an added danger by giving ignorant people a false feeling of security. Every part of the roadway must be watered, roof, sides and floor, and be kept wet continually.

In hot mines and in mines with certain kinds of strata in the roof and floor this method of watering is out of the question. In the mines in South Yorkshire it is found that on watering the roof or sides a huge fall occurs within a few minutes.

The reader is referred to the second report of the Royal Commission on Mining* (Cd. 4820) for a full description of the best methods of applying water to the roadways to render them safe from dust explosions.

METHOD 4.—STONE-DUSTING.

Safety by admixture of coal-dust with stone-dust is attained in some mines without any artificial means, owing to the method of working the seam. When such a method can be employed it is probably the best and most economical.

An illustration is provided by the Arley Seam of the Hulton Colliery; when a violent explosion in the other seams spread into this one, it was pulled up in about 20 yards. Dusts in this seam contained in some places very little stone-dust, nevertheless they were non-ignitable, whereas dusts in the other seams of the same mine were inflammable, although some of them contained more ash than the Arley dusts. Of the *pure* coals from the four seams, that from the Arley seam was the most inflammable. Hence it is evidently not the quantity of the stone-dust that counts so much as its *quality* and degree of fineness.

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* Also "Minutes of Evidence, Royal Commission on Explosions from Coal-dust in Mines" [C. 7401].

At many mines shale is being ground and put on the roadways to render them proof against explosion. It remains to be seen if this will have a sufficient restraining influence on a dust explosion. If the floor of a roadway is covered with fine stone-dust which, by the traffic or other means, is being constantly lifted into the air, the method will no doubt be effective. But in the author's opinion stone-dusting, as practised at many mines, is not a sufficient precaution. To put *coarse* stone-dust on the sides, etc., and allow it to become covered with pure coal-dust (as often happens) is a quite useless proceeding; with the help of the overlying coal-dust an explosion would be past before the stone-dust was thrown into the air. An ounce of fine stone-dust *floating in the air* of an intake haulage road is of more use in stopping an explosion than a hundredweight of coarse dust on the floor and sides.

The recent calamity at La Clarence Colliery (3rd Sept., 1912) showed that Taffanel barriers (a contrivance for putting ashes or water into the air during an explosion) failed to arrest a large scale explosion, though they had been effective in the experimental gallery.

In selecting stone-dusts care must be taken to avoid those that are gritty, since these might seriously injure the health of the miners. Also, in mines subject to gob-fires, it must be ensured that the stone-dust has no catalytic action in inducing gas and air to combine at a lower temperature, otherwise the last state may be worse than the first.

For a full description of stone-dusting the reader is referred to the excellent account of it in the Presidential Address of Dr. W. E. Garforth to The Institution of Mining Engineers (1912).

CHAPTER XI.

GOB-FIRES: THEIR PHENOMENA.

SPONTANEOUS COMBUSTION.

The spontaneous combustion of coal has been the subject of many researches, and much of our knowledge concerning it was obtained as far back as 1868. Yet, in spite of all the work that has been done, we are still without a satisfactory theory of its mechanism.

This want of progress is due to two main causes: firstly, our ignorance of the nature and constitution of coal itself, and secondly, the difficulty of carrying out experiments on a sufficiently large scale. It is impossible to obtain conclusive results from small masses of coal, and so far no one in this country, in a position to carry out experiments on a large scale, has been induced to undertake them.

Coal is far from being the only substance that will ignite spontaneously. Freshly made iron or lead in a finely divided state (pyrophoric), sulphides and polysulphides of iron, carbides of iron and nickel, zinc ethyl, phosphoretted hydrogen and phosphorus itself, will all ignite spontaneously on exposure to air, but in each of these cases the phenomenon can be explained quite satisfactorily on purely chemical grounds.

The spontaneous rise in temperature of decaying organic matter such as old potato tops, damp straw, manure and heaped-up grass from a lawn (which heating serves as the basis for the well-known "hot-beds" used by gardeners), is a more complicated phenomenon, depending for its initiation on bacterial action. But its mechanism offers little difficulty from the point of view of the chemist and physicist. Similar phenomena are the firing of hay, which has been stacked when too damp and the spontaneous ignition of cotton rags impregnated with oil- the "waste" which has been used in cleaning machinery.

The phenomenon has been observed even in materials of purely animal origin as, for example, the refuse from bone glue manufacture. Steamed bones, from which the glue has been extracted, contain 60-70 per cent. of moisture and a certain amount of residual organic matter. When piled up in large heaps this material remains apparently unchanged for several days—possibly for a month. Then a little steam appears near the top and this gradually increases until there is so much coming off (mixed with carbon dioxide and ammonia) that a spectator, ignorant of the phenomenon, would imagine there was a furnace beneath the heap. This high temperature continues until the bones are practically dry, and frequently, when such heaps are being carted away, parts become exposed where the heat has been sufficient to char the organic matter.

In all these instances of spontaneous heating of organic matter, the rise of temperature is originated by the action of bacteria, ferments or enzymes. But all such actions cease at a temperature below 100° C. (usually very much below 100° C.); they reach what is called the *optimum temperature*, which varies with the different kinds, and above this the activity of the bacteria, ferment or enzyme, is destroyed. Hence in those cases where heating much above 60° C. occurs it is necessary to conclude that the heating process, initiated by organisms or enzymes, is continued by ordinary autoxidation, and it may be carried to a stage at which active combustion sets in.

It is of importance to notice that there is little doubt that most coals are *endothermic*, that is at a certain temperature decomposition sets in and heat is evolved by rearrangement of the elements in the coal, without any outside material taking part in the reaction. The more oxygen a coal contains the more endothermic it is and the more liable to "spontaneous" heating.

Early Work on the Spontaneous Combustion of Coal.

Early experiments on the oxidation of coal were made by Fleck, Stein, Grundmann, Verrentrapp, Sauermann, and many others, but for present purposes it is not necessary to review their work. It will be sufficient to consider briefly the work of the two investigators whose results were of chief importance—Dr. E. Richters and Henri Fayol.

Dr. E. Richters was chemist at the Mining School of Waldenburg and published many papers on the chemical problems connected with coal. Powdered coal, previously dried, was heated in a current of air at 180°-200° C. and the changes carefully noted. The coal took up oxygen and increased in weight for 20 hours, then started to diminish in weight; at the same time it lost hydrogen as water and carbon as carbon dioxide, which were absorbed by reagents and weighed.

The coal used was a caking bituminous one from a mine near Waldenburg. In appearance the coal which had been heated was exactly the same as the original coal, but it was found that in all other respects it was profoundly changed. It had lost its coking property, absorbed water more rapidly and to a greater degree than the original coal, and had also increased in specific gravity.

The coal increased in weight 4·2 per cent.; at the same time it lost ·66 per cent. of hydrogen as water and 1·25 per cent. of carbon as carbon dioxide, these being estimated by absorption.

	Original Coal. Dry.	Coal after Heating.
Carbon	86·82	85·65
Hydrogen	4·26	3·52
Oxygen (+ N)	6·40	12·47
Ash	2·52	2·21
	100·00	104·21

From the analyses, 100 parts of coal lost 0·74 parts of hydrogen and 1·17 parts of carbon, and gained 6·07 parts of oxygen.*

Judging from the change in composition and properties of the coal, it would appear that the resin constituents had been converted into humus bodies.

Some different coals were examined in the same way by Richters with the following results in change of composition: *a*, *b* and *c* were coals from different parts of the same mine; *d*, *e* and *f* from different parts of another mine.

	Chemical Composition of the Dried Coals.				Sp.Gr.	Per cent. Increase.	Chemical Composition of the Heated Coals.				Sp.Gr.
	C.	H.	O+N.	Ash.		Weight.	C.	H.	O+N.	Ash.	
a	84·69	3·97	5·38	6·01	1·32	4·24	78·44	2·62	13·50	5·44	1·49
b	84·03	3·57	7·10	5·3	1·32	4·45	78·14	2·72	13·62	5·52	1·49
c	86·99	4·26	4·97	3·78	1·28	4·07	77·98	2·55	14·28	5·19	1·48
d	81·52	4·34	10·44	3·70	1·28	4·6	72·62	2·39	21·93	3·02	1·47
e	82·12	4·64	10·88	2·36	1·27	3·9	74·32	2·82	20·75	2·11	1·45
f	79·59	4·74	10·75	4·92	1·30	3·2	70·84	2·63	21·50	5·03	1·47

In another paper Richters states that one coal, which tested 4·8 per cent. oxygen, on being heated in air at 180°-200° C. gained in weight continuously for 72 hours and increased by 8·4 per cent.

Richters showed that the more hygroscopic moisture (*i.e.*, water which will not evaporate in dry air at ordinary temperature but requires 100°-105° C. to remove it) a coal contains, the more readily it takes up oxygen. Twenty grams of one coal he examined contained 5·1 per cent. moisture and absorbed 45 c.c. oxygen in 12 days, whilst a coal containing 2·5 per cent. moisture under the same conditions absorbed only 18 c.c. These two experiments were made at the ordinary temperature.

Richters experimented with coal in dry and in moist air at 15°-21° C. and found that perfectly dry coal absorbed oxygen (without giving off carbon dioxide) from dry air, as well as from air that was saturated with moisture. By mixing pyrites with an inert substance to the same percentage as it existed in the coal, he proved that the absorption of oxygen was not due to pyrites. This pyrites mixture absorbed *no* oxygen from dry air and only a very small amount from moist air, even when exposed for a long period.

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* The figures calculated from difference in analyses and those obtained by direct absorption of the carbon dioxide and water do not quite agree.

In a later paper Richters showed that coal absorbs carbon dioxide very rapidly, the volume taken up being three times as great as the volume of oxygen absorbed under the same conditions and in the same time. Samples which no longer absorbed oxygen took up carbon dioxide rapidly. When placed *in vacuo* the coal which had been saturated with carbon dioxide yielded up nearly but not quite all the gas that had been absorbed.

We are indebted to Henri Fayol* for the classical research on the spontaneous ignition of coal in heaps. His research occupied several years and the results were published in 1879 in a paper of 260 pages. These results were based on several hundreds of experiments carried out on the large scale. It is impossible here to give more than a few of his more important results and conclusions.

He experimented chiefly with coal from the Commentry Colliery in North France, near the Belgian frontier. It was a bituminous coal in which the ash, amounting to 0·5-15 per cent. with an average of about 7 per cent., was composed chiefly of clay, gypsum and pyrites spread in flakes. The average quantity of pyrites was 1 per cent., but in special picked samples it amounted to as much as 5 per cent.

Some of his results were:—

(1) Large lumps and pieces which will not pass a sieve with meshes of $\frac{4}{5}$th inch diameter, do not get hot spontaneously. Over 200 heaps of such pieces

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* *Bulletin de la Societe l'Industrie Minerale*, 2nd series, vol. viii., part 3, 1879; Abstract in *J. S. C. I.*, 1909, p. 760.

were examined, the heaps varying from 10 to 20 feet in depth, and no appreciable heating was found in any one of them.

(2) Slack that passes a $\frac{4}{5}$th inch sieve heats up and takes fire spontaneously whenever it is piled in heaps sufficiently large. Raw slack heats rather more rapidly than washed slack.

(3) Rough unscreened coal, fresh from the mine, behaves like the slack.

(4) Coal in fine powder, obtained from the slack washing, is rather less inflammable than screened slack. When the powder contains much clay it is still less inflammable, and this is the case also when any considerable amount of pyrites is present.

(5) The carbonaceous schists, obtained by picking out, take fire spontaneously like slack.

(6) The schists, separated during the washing, contain a considerable quantity of clay and are much less inflammable.

(7) Heaps formed of inflammable coal or of schist, built up slowly in successive layers of 3⅓ feet deep, do not take fire, no matter what the final volume may be.

When the heap is constructed in the ordinary manner, there is a direct relation between the height and the liability to ignite. He found that if the height was less than 6⅔ feet the heap never fired, while when the height exceeded 13 feet the coal invariably ignited.

Some further conclusions were:—

(8) Where the layer of slack is thin there is no rise of temperature.

(9) The temperature at any given time increases with the height. Passing from the lowest to the highest point there is a continuous rise of temperature in the coal.

(10) At a height of 10 to 13 feet the temperature rises steadily at first, reaches a maximum of 60°-70° C. (140°-158° F.), and finally falls again.

(11) At a height of about 13 feet, or slightly above this, the temperature continues to rise steadily. During the third month, or thereabouts, steam begins to rise from that part of the heap at which the height is greater than 13 feet. This is succeeded by a colourless gas that smells strongly of paraffin and then, after a few more days, smoke begins to issue from the sides of the heap. This smoke generally appears about half-way up the side of the stack at the place where it is highest.

On examination of the heap, at the stage when smoke begins to appear, it is found to contain three distinct zones:

(1) A lower central zone, where the temperature is 120°-150° C.

(2) A zone surrounding the first but at considerably lower temperature.

(3) The exterior zone, which is at about the ordinary temperature.

If the heap is cut across, to expose the core of heated coal, yellowish white fumes are evolved, the temperature quickly rises to 200°-300° C. and ignition takes place.

No matter from what part of the mine it was taken, or what was its nature and ash contents, the coal underwent the above changes when heaped in the open. And this was quite independent of atmospheric influences, *i.e.*, of the temperature, pressure and amount of moisture in the surrounding air.

The United States Bureau of Mines have issued a preliminary report on the deterioration and spontaneous heating of coal in storage. Of 220 cases of spontaneous firing reported to the Bureau, 95 were in semi-bituminous, low volatile coal of the Appalachian region, 70 in higher volatile coals of the same region, and 55 in Western and Middle Western coals. This shows that even the "smokeless" variety of coal is liable to spontaneous heating.

In the large piles stocked at Panama, Appalachian coals, with 17-21 per cent. volatile matter, give a great deal of trouble from spontaneous fires. Several large works report that their low volatile coals are more troublesome in respect to spontaneous fires than the high volatile gas coals. But the high volatile coals of the West are usually very liable to spontaneous heating.

The oxygen content of coal appears to have a direct relation to the avidity with which coal absorbs oxygen: high oxygen coals absorb oxygen readily and therefore have a marked tendency to spontaneous combustion.

Fayol investigated the spontaneous combustion of small quantities of powdered coal exposed to air heated at various temperatures. Gas-making coals (powdered) took fire in five hours at 100° C., in two hours at 150°, in forty minutes at 200°, and in a little over a minute at 400°. Anthracite (powdered) took fire in four hours at 200° C. and in 30-40 minutes at 400°.

The order of inflammability was found to be: (1) lignites, (2) gas coals, (3) coking coals, (4) anthracite.

The state of division of the coals has a great influence on the temperature and time required for spontaneous combustion. In fragments of 1 centimetre and over, none of the coals took fire below 400° C. Dust composed of fragments measuring half a millimetre took fire at 200° C., except in the case of anthracite. When the coal was in the state of impalpable powder, whether it was lignite or gas coal, it caught fire at 100° C. Pieces measuring 1 centimetre did not catch fire unless there were several of them.

On the other hand, a single piece, measuring 10 centimetres on the edge, did catch fire; it first broke up under the action of heat, and it was in the cracks, probably in the dust lying in them, that the fire started.

At 400° the coal and dusts broke into flame on the surface. At 200° and below, the fire did not break out at the surface but at a depth of 1-2 centimetres; a crust was formed at the top and smoke given off after a certain time, then on breaking through the crust it was found that the coal below was incandescent.

Fayol's final deductions on the spontaneous combustion of coal were:—

(1) The first essential cause of spontaneous combustion of coal is the absorption of oxygen from air by the coal.

(2) The best conditions for spontaneous heating of coal are: a mixture of fragments and of dust, a high initial temperature, a large quantity of coal and a certain proportion of air.

(3) The conditions opposing spontaneous combustion of coal are: storing the coal in large pieces, preserving a low temperature, stacking small quantities and ensuring either complete absence of air or very effective ventilation.

Phenomena of Gob-fires.

The phenomena described by Fayol of the oxidation of small coal in heaps, from the commencement of heating to the smoke stage, are strikingly similar to the symptoms of many gob-fires. The appearance of steam in the heaps corresponds to the "sweating" in the mine; the paraffin smell is common to both and is succeeded by smoke in the case of gob-fires just as in the oxidation of heaps.

All three stages have been observed in very many gob-fires in the wastes of coal mines. In the case of gob-fires the factor corresponding to the height of the heap is the distance between the gates or roads, across which a small current of air may be supposed to be drawn by the difference of pressure.

The period of about three months, mentioned in Fayol's paper, is also very significant. When examining a gob-fire the author has often asked the question, "How long is it since this waste was made?" The answer has been almost invariably, "About three months or a little more." It has very seldom been less than three months, though in one or two abnormal instances the age of the waste has been *supposed* to be much less than this, "supposed" because it is possible for a tub of cooled gob-fire dirt or slack to be gobbed in another place although, naturally, very great care is taken to prevent any such occurrence. But at least two fires can be traced to this having been done, and it would appear desirable that in pits subject to these fires, special tubs should be provided for taking out the heated coal and dirt, so as to reduce the risk of any of it being gobbed in another part of the mine by accident.

Whatever the mechanism of the action may be, we know definitely that most varieties of coal absorb oxygen (and nitrogen) from the air, especially when freshly mined or powdered, and that the rapidity of absorption is proportional to the fineness. If the heat generated by oxidation is concentrated and cannot be easily dissipated, the mass will gradually rise in temperature, and as this happens the amount of absorbed oxygen increases, for we know from many experiments that the rate of absorption of oxygen by coal increases rapidly with rise of temperature; the coal absorbs oxygen and rises in temperature just as a rolling snowball gathers snow.

In its first stage the action results in an absorption of oxygen; practically no carbon dioxide is evolved and the coal increases very appreciably in weight. In the second stage, which proceeds at a higher temperature, the hydrogen of the coal is oxidised to water by a further quantity of atmospheric oxygen. A little carbon dioxide and a trace of carbon monoxide are also evolved, together with the smell of paraffin, but the combustion of the hydrogen part of the coal is the chief reaction. At a still higher temperature oxides of carbon are evolved in considerable quantities and are accompanied by a peculiar smell, known to mining people as the "gob stink." This is followed at about 150° C. by the production of smoke. At this temperature coal in bulk will, on exposure to air, heat up rapidly and become red-hot.

When such coal at this temperature ("black" heat) is uncovered in the mine, a curious phenomenon is sometimes observed: the coal becomes red-hot in little patches and often in veins, the glow spreading along the exposed face in strings of red-hot fire. On careful examination the veins so affected are found to consist of *dant* or *mother of coal*.

VARIETIES OF GOB-FIRES.

It is a fact known to all who have had much experience of these fires that every heating has its own individual peculiarities. No two gob-fires are exactly alike and each one has to be treated according to its own characteristics: but, neglecting minor differences, it has been found that there are certain broad resemblances among those fires that originate in similar situations. They may be classified as of three main kinds, viz.:—

(1) Those which occur in the unworked coal.
(2) Those which originate in the goaf, *i.e.*, in the coal left, either because its removal would be dangerous or because it would not pay to extract it.
(3) Those which originate on a fault side where some coal is often left; these may be either in goaf or in untouched coal.

Those of the first variety appear in the solid coal left in the form of shaft pillars or pillars needed to support buildings, railways, etc., and are usually found near the roads driven through them. Sometimes they occur on the edge of these pillars, in the goaf. The heating originates in the more or less vertical breaks or large cracks that are formed near the edge of the pillars by the weight of the overlying strata. It is supposed that air circulates through these breaks, which are filled with fine coal-dust, it is this dust which heats up and fires. The breaks are approximately parallel to one another and are generally a few feet from the road side or goaf, though they may be yards back, and the coal is often sufficiently hot to ignite on exposure to air.

Heatings of the second variety originate in the coal or shale left in the waste and are generally supposed to be due to a short-circuiting of air through such waste, from the intake to the return road. They all have one feature in common, which is that the roof has, by some means, been held up and has not crushed the waste closely enough to prevent this short circuiting. Roof pressure militates in two ways against the occurrence of gob-fires: it checks air leakage and it promotes contact with the adjacent strata, so that any extra heat in the waste is more quickly conducted away.

The above explanation is supported by the fact that this variety of heating is often caused by a fall at the face or in one of the roads or gates; this fall interferes with the normal ventilation, increases the amount of air that is short-circuited, and develops a serious fire. Moreover, it has been observed on several occasions that when the ventilating pressure (the water gauge) has been increased, in order to remove a troublesome quantity of gas in a particular district, heatings have rapidly developed in several distinct districts and become serious enough to necessitate digging out. Conversely, it has very frequently happened that heatings at an early stage have been checked and extinguished by diminishing the ventilation in the affected district.

In many instances it has been observed that the first signs of a gob-fire have shown themselves, not in the return, but in the intake side of the waste, and have appeared soon after a big fall in the atmospheric pressure. It is hardly possible that in these cases the heating is due to a short-circuit of air.

The appearance of the first signs (smell or smoke) in the intake is probably due to the fact that there is only one outlet for the products of combustion. Such places (and there must be many of this nature in the wastes of a mine) resemble a bottle in that they have only one entrance and exit for the air. Heatings in them *must* get the air by diffusion or by the ventilation of the goaf by change in pressure of the atmosphere and *not by short-circuiting*.

One of the first signs of the development of a gob-fire is *sweating*—the appearance of moisture on props and stones, accompanied sometimes by a musty smell. Any air coming off, if tested, is found to be low in oxygen contents, with no corresponding volume of carbon dioxide to explain its removal, as there is when the oxygen has been used up by respiration or by the combustion of an oil lamp or candle. It is, therefore, possible to distinguish the oxygen reduction due to the removal by coal from that due to the removal by men and lamps.

The next stage is the appearance of a colourless gas with very little oxygen, some carbon dioxide and a little carbon monoxide, together with what has been called the paraffin smell, but which is often more like the smell of petrol. This is followed frequently by the smell of warm timber, and finally by the true "gob stink"—a characteristic odour impossible to describe. It can be produced quite easily by heating bituminous coal at 120° C., or thereabouts, in a tube and passing a current of air over it. The gob stink is accompanied by gas with very little oxygen and considerable quantities of carbon dioxide and carbon monoxide—the latter often in dangerous quantities for breathing, even when it has been diluted by the fresh air in the roads.

The explanation of the paraffin stage mentioned above is that the coal, somewhere in the waste, has become warm enough to throw out into the air hydrocarbons, higher than methane, in considerable quantity. These higher hydrocarbons are contained in the coal or are formed from the coal substance by the action of air.

In a recent experiment some soft bituminous coal, which had had most of its methane drained off by standing in air for some months, was powdered and subjected to heat at 100° C.; after an hour the air in contact with the coal was tested and found to contain over 12 per cent. of inflammable gas, which was found to consist of higher hydrocarbons.

In the old goafs of mines the inflammable gas contains these higher hydrocarbons, and it is the presence of these different hydrocarbons that makes the well-known difference in the appearance of gas "caps." There is sometimes such a quantity of higher hydrocarbons in old fire-damp that white caps are formed, but this is very abnormal. These higher hydrocarbons are very much more dangerous than methane, the lower explosive limit is much less, being only 1½-4 per cent.; also the temperature of ignition is very much lower than that of methane mixtures.

Traces of higher hydrocarbons can be detected in the fire-damp which occurs in most seams, but at the fresh coal face the fire-damp given off is chiefly methane, and there is not a sufficient quantity of higher hydrocarbons to make it perceptibly more dangerous than ordinary fire-damp.

The third variety of heating occurs at a fault side and is as a rule the most difficult and dangerous kind to tackle. Much of the difficulty is due to the treacherous nature of the roof. Falls are frequent and often bury the fire for a day or two before the men can get at it again; meanwhile it increases considerably in extent and often the fall is found to have fired too. It is quite common to find, at faults, coal which has been powdered by the grind it has been subjected to, and it is very likely that it is pockets or layers of this which start the fires at fault sides so often. There is, of course, also the fact that, however carefully worked (and extra care is generally given to such parts because of the well-known liability to fire), the roof at fault sides does not settle so quickly or evenly as in a normal goaf.

INFLUENCE OF WEATHER.

Fayol in the course of his experiments found that when coal was stacked in heaps in the open, and spontaneous heating occurred, the phenomenon was independent of the weather, or was so slightly affected by it that its influence could not be detected.

This is not the case, however, with gob-fires in mines. It has long been known that damp, changeable weather is particularly favourable to the appearance of gob-fires, and their abundance in the South Yorkshire coalfield in the spring and summer of 1912 will long be remembered. In an average year it is during the damp, foggy weather of late autumn and winter that gob-fires are most prevalent.

But it must not be overlooked that dampness is not the only characteristic of changeable weather. In the author's opinion a more important factor than dampness is the rapid alteration of pressure that occurs during such periods, the barometer rising and falling several times in a day. Moreover there are many slight alterations which are not seen on the ordinary barometer or on a barograph chart, but which can be detected by a specially sensitive instrument. It is well known that miners do not need to be told of a rise or fall in the barometer; they can tell by the gas movements in or out of the goaf long before any change is registered by the mercury column.

It has often been observed that stacks of coal blaze up or smoke after a shower of rain. This is one of the reasons why so many people "got the impression" that moisture favoured spontaneous combustion in coal. It is often seen in the shale heaps at pit tops—heaps that have been merely smouldering for days will blaze up after a shower of rain.

Recent observations have shown that there are small sharp up-and-down movements in the atmospheric pressure during a shower of rain, and it is no doubt these movements, which supply the heated coal or shale with fresh air and cause the increased activity. In the case of the coal and slack heaps, these were doubtless previously heated up inside but not sufficiently so to be noticed, and the quick up-and-down movements during the shower hastened the process and made the heating visible.

The British Royal Commission of 1876, to inquire into the Causes of Spontaneous Combustion of Coal, came to the conclusion that wet coal was more liable to spontaneous ignition than dry. But when the evidence is closely examined, as it was by the New South Wales Commission of 1900, it appears that of the 26 answers received to the effect that wet coal was dangerous, 25 of them were based on "*general impressions*" or hearsay evidence, while the 26th was not tested by cross-examination. "The opinions referred to were not held by scientific men but by those engaged in the coal trade. . . . All such views, it seems to us, must now be definitely abandoned."*

These points are very important, as, in spite of the more rational views of the New South Wales Royal Commission, based on experiments, it is evident that the 1876 report of the British Royal Commission still holds sway with many mining men. This is due no doubt to the fact that one set of opinions (1876) has found its way into text books, while the more recent evidence has not yet been widely disseminated.

It is the author's experience that most mining men are "*under the impression*" that moisture or water increases (or "would increase" expresses better their state of mind) the number of spontaneous heatings in mines subject to gob-fires. This belief has also been expressed many times in discussions on papers on gob-fires occurring in the Staffordshire mines, especially in the Bullhurst Seam. There *may* be some *evidence* to bear out these opinions, but none has yet been produced, so far as the author is aware. The weight of opinion amongst those who store coal on a large scale is certainly in favour of the idea that moisture promotes spontaneous heating. But in not one of the many cases of spontaneous combustion observed by the author, or by the investigators of the U.S.A. Bureau of Mines,* or of the Royal Commission, New South Wales, referred to,† could it be proved that moisture had been an inducing factor.

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* *Trans. N. of England Inst. of Min. and Mech. Eng.*, *1901*, 49 [*b*], 112-114. Abstract, *J. S. C. I.*, *1901*, 789, 790.

It is, however, possible that the physical influence of moisture on fine coal, in causing closer packing of dust or small pieces, does in some cases aid spontaneous heating.

Quick alterations of the atmospheric pressure must have a considerable influence in the formation of an explosive mixture in the goafs and roads of a mine, and they have certainly led to the outbreak of many gob-fires.

INFLUENCE OF TIMBER.

When gob-fires of any size appear in the goaf or on a fault side, it is usually found that props have been left in. The timber so left is regarded by many people as the origin of the fire that subsequently occurs. Such timber would certainly tend to retain an open space around it for some time and, if the adjacent coal did heat up, the timber would no doubt ignite at a lower temperature than the coal itself.

There are several cases on record of a pit prop being found blazing—a pit prop actually in the roadway of a mine. On examination it has been found that the ground has warmed up round it. In most mines a great quantity of timber is left behind in the waste. It is absurd to allow this in a pit subject to gob-fires. It would repay the colliery company to appoint an official whose sole business was to be responsible for the withdrawal of all timber and to see it done. In addition to this, all timber used in a doubtful district at fault side, etc., should be fireproofed.

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* Technical Paper, No. 16, by Porter and Ovitz, U.S.A. Bureau of Mines.

† N.S.W. Report of Royal Commission appointed to inquire into the Cause of the Dangers to which Vessels carrying Coal are said to be peculiarly liable, and as to the best means that can be adopted for removing or lessening the same. May, 1897.

We know also from many cases on record that timber in flues takes fire at a very low temperature. The explanation given* is that during one or many winters the wood gets gradually charred and converted into a material which absorbs oxygen and water from the air during the summer, and this ignites at a low temperature when fires are started again. A wood which originally has an ignition temperature of, say, 650° C. may have it lowered as much as 200° C. by very slow charring at 200°-250° C.

But it is very improbable that the timber is the primary cause of heating in gob-fires. This is indicated by the experiments of Fayol (in which no timber was present,) and also by the experiments carried out in connection with the New South Wales Commission, 1900, on the spontaneous combustion of coal cargoes. The following extract from this report is of considerable interest:—

> "In order to try the influence of moisture, two cubical bins of 21 feet edge were loaded with the same kind of coal under exactly the same conditions, except that one bin was loaded with dry coal whilst in the other case a stream of pure water was continuously played into the bin, in such a way as to saturate it thoroughly. The quantity of water used was sufficient to cause a small stream to flow from the bottom of the bin, but not sufficient to wash out any considerable quantity of fine dust.
>
> "For the purpose of observing the temperatures, thirteen thin galvanised iron tubes, about 2 inches diameter and 0·018 inch thick, were placed vertically in each bin before loading. The bins were filled on December 2nd, 1898.
>
> "In the dry bin the temperature rose rapidly, and on February 13th, 1899, at 8 feet from the surface, it was

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[*] After Prof. Vivian B. Lewes.

> so high that the solder connections of the thermometer were melted. In the central tube, at 4 feet from the surface, the temperature was 135° C. In all the other tubes the temperature was much lower, the highest being 87° C. At this stage the bin was flooded with water and the hot coal was removed. The heating appeared to be confined to a spot immediately in the vicinity of the central tube.
>
> "With the wet bin the experiment was continued until April, 1899, but no sign of heating could be observed. From January 27th onward there was a steady decline in the mean temperature."

No timber was present in the coal during these experiments, nor was any mixed with the coal in Fayol's experiments, yet ignitions invariably occurred under certain conditions. Moreover, there is no case recorded of a stack of timber taking fire spontaneously.

This evidence shows that timber does not originate gob-fires. Nevertheless its presence certainly assists the fire, and makes its treatment much more difficult by reason of the pungent fumes evolved. Moreover, heated timber is much more likely to blaze up, when exposed to air, than coal at the same temperature.

Consequently it is of great importance, in a mine subject to gob-fires, that no timber should be left in the goaf. And if timber buried by a fall can possibly be extracted, this course will be found cheaper in the end. A few pounds spent in labour in recovering timber so lost may save as many hundreds a few weeks later.

Enlightening results would probably be obtained if the bin experiments, described by the New South Wales Commission, were repeated with various materials from a mine subject to spontaneous heatings. In some of the bins a few pieces of wood props could be introduced in order to trace the effect of timber. By means of bins of this size it would also be possible to carry out experiments on methods of *preventing* rise of temperature in stacked coal.

The Royal Commissioners, who had these bin experiments made, had the utmost difficulty in obtaining the supply of small coal for the investigation; most of the collieries refused to supply material as they thought the experiment, if it resulted in a heating, would prejudice shippers against their coal. The supply finally obtained was got only when the Commission agreed not to allow the source of supply of the coal to become known. There is very much of this kind of prejudice amongst English colliery managers, and perhaps it is natural, but as long as it persists very little progress will be made. It would almost appear that such experiments could best be inaugurated by the shippers of coal cargoes, or perhaps one colliery might try coals from other collieries. There is very little doubt that all coals, with the possible exception of some anthracites, are subject to spontaneous combustion. The problem is to find the simplest method of prevention and apply it to mines and coal cargoes.

INFLUENCE OF PYRITES.

Iron disulphide is dimorphous, existing in two distinct cystallographic forms, viz., pyrites, in the regular system, and marcasite in the rhombic. Usually the variety found in coal is pyrites; marcasite occurs very rarely. Pyrites is not easily oxidised but marcasite readily takes up oxygen, especially when it is impure and contains arsenic.

Although it was at one time supposed that the oxidation of iron pyrites in the coal supplied the heat necessary to start gob-fires, this belief (it was never anything but a "belief") is now almost abandoned, many researches, by different chemists, having shown that it is untenable. Reference has already been made to Richters' experiments on this point.

After considering much evidence on this matter, the New South Wales Commission, in 1900, said that they "attach no importance to the influence of iron pyrites" in the spontaneous ignition of coal.

Prof. V. B. Lewes,* after carrying out many experiments on the spontaneous combustion of coal stored in bulk, showed that the oxidation of the pyrites present plays a very subsidiary part, the chief factor being the surface condensation of oxygen in the pores of the coal, and the action of the condensed oxygen on the hydrocarbons present. He suggested that carbon dioxide cylinders, with plugs of fusible metal, should be embedded in cargoes of coal in order to check spontaneous heating.

In the technical paper, No. 16, of the U.S.A. Bureau of Mines (1912) the following passages bearing on this subject appear:—

> "Sulphur has been shown by the Bureau's investigations to have only a minor effect in most instances. On a number of occasions samples of coal, from the places in a pile or bin where the heat was greatest, have been analysed, both for total sulphur and for that in the sulphate or oxidised form. The difference between the two determinations—or, in other words, the unoxidised sulphur—was in no case less than 75 per cent. of the average total sulphur in the coal which had not been heated. In other words, not one-fourth of the sulphur had entered into the heat-producing reaction. . . . ."
>
> "A Boston Company, that uses a Nova Scotia coal containing 3 to 4 per cent. sulphur, has much trouble with spontaneous fires in storage piles. Analyses of a number of samples, taken by representatives of the Bureau of Mines from exposed piles in which heating had occurred, showed that 90 per cent. of the sulphur was still unoxidised."
>
> "In certain laboratory experiments in which air was passed over samples of coal heated to 120° C. enough heat developed to bring the coal almost to ignition point.

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* *J. S. C. I.*, 1904, p. 1203 (Abstract).

Subsequent analysis showed practically no increase in the sulphate or oxidised form of sulphur and practically no reduction of the total sulphur in the coal."

WORK OF HALDANE AND MEACHEM.

In connection with this question of the influence of pyrites, and other chemical problems bearing on gob-fires, the investigations of Haldane and Meachem* at Hamstead Colliery merit some criticism, for, owing to the eminence of these investigators in other fields, their work has received wide publicity and has often been quoted as authoritative.

Briefly stated, some of their conclusions were:—

(1) A very large amount of heat, often sufficient (if not otherwise absorbed) to heat the air current to a temperature of 212° F., is always being generated in a mine, and this heat is almost entirely produced by oxidation of material in the mine.

(2) Usually the heat produced greatly exceeds in amount that withdrawn by the air current, so that the temperature of the mine, or some parts of it, is above that of the adjacent strata.

(3) The disappearance of oxygen and liberation of heat in the mine are probably due, largely at any rate, to oxidation of pyrites, while the liberation of carbon dioxide is probably due to the action on carbonates of the sulphuric acid so formed.

Some of these results are so peculiar, and so greatly at variance with the results of other investigators, that the author was led to study in detail the experimental methods employed by Haldane and Meachem. His conclusion is that their method was unsound and their inferences almost wholly fallacious.

The depth of the mine was about 1,800 feet, and the mean annual temperature at the surface was 49° F., while that at the bottom of the intake shaft was 60° F. The heating effect due to compression was 10° F. (5·5° F. per 1,000 feet), the heat extracted from the shaft walls was therefore 1° F. Along the intake, passing away from the downcast, the temperature rose 6° F. in 300 feet, and at 600 feet it was 70° F., while in the workings it was frequently 80°-85° F.

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* Haldane and Meachem, *T. I. M. E.*, vol. xvi. 457.

Haldane and Meachem state that the natural ground temperature at the bottom of the mine was 66° F.! and they base their first and second conclusion on this foundation, together with the fact that the air showed a deficiency of oxygen but did not contain an amount of carbon dioxide that corresponded to this deficiency.

Now in a mine 1,800 feet deep the natural temperature should be about 90° F., and no doubt in the Hamstead mine it is much nearer to that figure than to the value given by Haldane and Meachem. The cause of the discrepancy becomes evident when their method of taking the temperature is examined.

They obtained their temperature in the following manner. A borehole was drilled 10 feet into the fresh coal-face and a minimum thermometer, mounted on a long stick, was placed at the far end of the hole. The mouth of the hole was then stopped with a piece of clay, to prevent the air current affecting it. The thermometer was left there two or three days and then withdrawn, the minimum temperature registered being taken as the temperature of the strata.

This method would give an entirely erroneous value, for the gas in the coal, being under great pressure, would ooze out at the end of the borehole and during its expansion would cool the adjacent coal and the thermometer. Hamstead is described as a mine that contains very little gas, but one of the analyses given shows the presence of 0·28 per cent. of marsh gas in a main return, so there must have been plenty of gas in the coal itself.

The further assumption, that the oxygen removed is absorbed by pyrites, is now known to be incorrect. At the temperature of the mine air, 80°-85° F., the oxygen is occluded by the coal and then partially combines with it, with formation (so it is said) of humic acid, a reaction which apparently evolves very little heat. Another portion of the occluded oxygen appears slowly to oxidise the methane, which is also occluded, the coal itself acting as a catalyst.

Theory of the Origin of Gob-fires.

Fayol's experiments throw much light on the mechanism and progress of gob-fires, but they give no clue to the origin of these fires. Indeed, no conclusive evidence has yet been obtained to account for the spontaneous combustion of coal. It is, however, the author's opinion that many gob-fires are originated in the same manner as spontaneous combustion is caused in other carbonaceous materials, *i.e.*, by the action of bacteria, ferments or enzymes.

Though at first sight it may seem somewhat extravagant, this opinion has much to support it, quite enough, in fact, to establish its claim to be used as a working hypothesis. It has already been pointed out[†] that ferments or enzymes, or both together, must have played an important part in the formation of coal. We know, too, that the formation of methane still goes on in the coal after it has been mined.[‡] Finally, it has been shown that many kinds of bacteria can live and thrive on coal with the production of methane (and carbon dioxide).[§]

With this evidence it is not difficult to imagine that the initial rise of temperature may be due to the action of such organisms or enzymes. Under different conditions (*e.g.*, in the presence of air), the bacteria or enzymes already present may begin to act in a different way; or it may be that new ferments or enzymes are introduced by the ventilating current and find coal a good material on which to thrive.

[†] See p. 132.

[‡] Porter and Ovitz, "The Escape of Gas from Coal," Technical Paper, No. 2, U.S.A. Bureau of Mines, 1911.

[§] See E. Galle, *Bakter in Parasitak art Central Blatt*, 1910, 28—461, 473.

The usual end of bacteria and ferments is death or extinction by their own products. Under favourable conditions autoxidation will then set in on the warm products and dead bacteria, and this may raise the temperature sufficiently to start energetic oxidation in the surrounding mass of carbonaceous material and finally end in ignition.

In some coals, such as anthracite, the process of condensation has no doubt gone on as far as the ferments can take it, so that no further trouble from heating is likely to occur in such coal from bacterial or ferment action. This is probably the reason why gob-fires do not occur in anthracite seams.

In other kinds of coal, however, the action was still going on when the mother substance was submerged and in many seams it may still be going on.* In these varieties autoxidation is quite likely to set in, and under favourable conditions sufficient heat may be evolved to fire the coal.

On page 138 it has been pointed out that (according to the U.S.A. Bureau of Mines) it is coal rich in oxygen that is most liable to heat up and fire. This same view is expressed by Dunstedt and R. Buriz,† who say "Spontaneous combustion is due to oxidation of unsaturated organic compounds of the coal; the more inflammable coals contain more oxygen and a certain degree of oxidation is necessary to render further oxidation and spontaneous ignition possible."

They state that the final product of the slow oxidation is humic acid, which is present in greater quantity in the more readily inflammable coals. Also that neither the mineral constituents, pyrites, organic sulphur, nor nitrogen, appear to have any effect.

People who have had long experience of gob-fires through fighting them year after year, possibly for a generation, have described some of these fires as spreading just like an infectious disease. A heating on one side of the road was followed by one on the opposite side, and this by a third, and so on, even when there was no visible connection between the burning portions; it seemed as if the influence of the first was transmitted through the air and other gases present.

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* Bacteria can live under pressures up to 2,000 atmospheres.

† *J. Angew, Chem. 1908*, 21—1825, 35. Abstract in *J. S. C. I.*, *1908*, 929.

These facts taken together are sufficient to show that the author's view has much to support it and that it may be helpful in further investigations into the origin of gob-fires. The three zones which Fayol describes also point to the combustion being initiated by the action of bacteria, ferments, or enzymes. Such action would spread outwards as the second stage of autoxidation set in on the warm products left in the interior by the initial action. If the heating was due to autoxidation alone one would expect the coal in such a heap to be warmed up gradually from below and to reach a maximum temperature near the top, without the appearance of distinct zones.

It is perhaps as well here to recall attention to what has been stated (on page 31) with regard to catalysts. There is no doubt that coal (and coal-dust) is a powerful catalyst, and it is not by any means unlikely that this catalytic action is sufficient to explain the first heating of coal, especially of finely divided coal,* in a confined space where the heat cannot be dissipated.

There is no sharp line of division between ferments and catalysts; certain inorganic catalysts have so many of the properties of ferments that they are called inorganic ferments; they have the power of causing an increase in the rate of particular reactions at certain temperatures, just as ferments and enzymes do when below their optimum temperature.

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* At the inquiry into the gob fire and disaster at the Jamage pit (working the Bullhurst seam) the manager stated that it was usually in the bottom coal that heating took place, and generally where they had *a band of soft fine coal like blacklead* 3 to 5 inches thick. In North Staffordshire the "Hussle" (a highly carbonaceous shale) was regarded as dangerous, but no eating in it had been noticed in the Jamage pit.

All that is necessary to get spontaneous combustion of coal, in a variety that is subject to such, is to have sufficient air—not too much and not too little—and to have the coal in sufficient mass or in a sufficiently warm place to prevent the heat being dissipated. In any kind of coal one can get "spontaneous" combustion by placing it on even moderately heated pipes, if there is a sufficient mass of coal.

The difference between the two cases is, in the author's opinion, that the first kind is open to attack by air at ordinary temperatures, and this is probably due to enzyme action following the occlusion of air; while in the second case sufficient heat must be supplied to start the rapid oxidation.

CHAPTER XII.

GOB-FIRES (CONTINUED): THEIR TREATMENT.

Apart from its scientific interest the problem of gob-fires is of great industrial importance. These fires are very prevalent in North and South Staffordshire and Warwickshire; in North Staffordshire they are dangerous, as they break out in a gassy seam. They occur also in Fifeshire, Midlothian, Lanark, Sutherland, Shropshire, Derbyshire, North Wales, and Lancashire, and in several of the Yorkshire seams, though only occasionally in gassy seams, except in the Doncaster district, where they are very frequent in the Barnsley bed.

In recent years their removal from certain mines has cost thousands of pounds annually, and now they are so prevalent in some parts that the very existence of a number of mines in those districts is threatened. Nor can their cost be estimated in terms of money alone: they are a constant menace to thousands of workers, and they add enormously to the anxiety and labour of those managers and officials who have to deal with them.

It is of course uncertain whether an exact knowledge of their origin and mode of development would enable us to prevent their occurrence, but we do know, by analogy, that a cure is more difficult when the cause of a trouble is unknown. Large scale experiments, of the kind indicated in the previous chapter, should certainly be undertaken; they would in all probability be found to pay very quickly for themselves.

The urgency of the problem has compelled the attention of managers and, although no scientific attempt to prevent these fires has yet been made, useful records have been compiled of their phenomena and of the practical experience gained in fighting them. In the journal of the Institution of Mining Engineers (vol. xviii., p. 154) there is an account of sixteen of these fires, recorded by Mr. W. H. Chambers, and the facts he gives emphasize the subtle nature and persistency of gob-fires.

For example, one of these fires at Denaby caused the workings to be abandoned in 1879, the roads being sealed up some 450 feet from the bottom of the shaft; yet in order to end this fire it had eventually to be dug out in 1892! Again, in the case of a fire (No. 16) at Cadeby Pit, there was an explosion following on a fall, yet no fire could be seen and no gas detected either before or a few minutes afterwards. It was found in this case that very little of the top coal was on fire but that the shale above it was white hot. Possibly the cause of this explosion was a spark or series of sparks generated by friction between the rocks in the fall. The whole paper supplies a very useful fund of information for future investigators.

It would be out of place here to give a detailed account of the methods in use for combating gob-fires. These methods will be considered chiefly in connection with the chemical problems they involve.

It is generally agreed that, in longwall advancing, when a heating has been approximately located and the roads are good, the best course is to get at it as soon as possible and dig it out. The ventilation should be at once reduced, provided that the district is sufficiently free from gas. If the roads are not good (and this is frequently the case), a tight stopping of bricks and mortar should be put up as quickly as possible, in addition to reducing the ventilation, while the roads are made good enough for the dirt to be taken out. When this has been done, a scouring can be commenced in order to find the exact situation of the heated material. The location of this is by no means an easy matter: it requires much skill and practice. A good supply of damp sand should be kept at hand and put on the hot coal if this shows any tendency to blaze up.

The gases evolved from a gob-fire are of a very poisonous nature; they may contain as much as 8 per cent. of carbon monoxide as well as some sulphuretted hydrogen. Moreover, there is very good reason to believe that they are much more inflammable than the marsh gas found in mines under normal conditions. Consequently very great care must be taken that the gas evolved from the heating (it is known as *white damp*) is not allowed to mix with air *near the hot coal*. It should be led away by an iron pipe fixed near the roof of the scouring and, after being taken some distance from the heating, should be diluted with a sufficiently large volume of air to render it harmless.

With ordinary marsh gas the limits for an explosive mixture are between about 5 and 13 per cent. of gas, but with these gases the limits are probably as wide as 4-28 per cent., *i.e.*, the gas mixed with air in any proportion between these two values will form an explosive mixture. Also it is probable that such mixtures can be ignited by red-hot coal, even when there is no blaze. Several small explosions, which have taken place at gob-fires, must have been initiated by red-hot coke or coal.

Another precaution, which should always be taken at these heatings, is to remove coal-dust from the sides, beams and floors in the district, and to spread a good covering of stone-dust before starting the scouring. Then, if an ignition of gas does unfortunately take place, it will be confined to a small area and not be propagated or extended by coal-dust.

When a gob-fire gets out of control, driving the men back, an explosion is likely to take place, especially if the ventilation near the fire is "good": explosion after explosion has been known to occur under these conditions. Therefore, after one explosion has taken place, it is advisable to act on the assumption that a second one will occur (after an unknown interval of time), and that this will be followed by a third, unless the ventilation is sufficiently reduced.

It is the possibility of these flashes (which are often beyond control, since they originate in the waste which is on fire) that constitutes one of the chief dangers of gob-fires. Sometimes the flash comes without the slightest warning, when there is no gas in the road or scouring and when the men are actually at work digging out the hot material.

The only way of tackling a fire, which has got beyond other means of control, is to brick off the intake and return roads to the district.* Even after bricking off, with a large portion of waste and roads in the enclosed or sealed district, the fire must always be a source of danger. The possibility of an explosion remains and there is very considerable danger of one just after closing the stoppings. If an explosion does occur and the stoppings are then replaced quickly, there will probably be no further explosions and the fire *may* eventually die out for want of oxygen. A gob-fire can, however, exist and spread on very little air, and in mining, with advancing longwall face working, it has been found from experience, as shown in the paper previously referred to, that it is best and safest to dig out the hot material.

Attempts have been made on several occasions to avoid the digging out by gobbing up the roads in the district and putting stoppings at intervals, the treatment being extended for 100 yards or more. After a few weeks or months however, it has been found that the fire has spread right through this distance and advanced up to the last stopping.

The risk of this method of stopping and gobbing up with shale and dirt is that the danger merely becomes concealed. There is practically no gob stink and the fire appears to be out, although in reality it is extending rapidly, and in the end it will be compulsory to dig it out. When such a stopped-off heating is dug out, it is sometimes found that all the shale and dirt is red or even white hot, while the coal at the sides is practically unburnt. This phenomenon is an interesting example of surface combustion: air has leaked in and mixed with the gas from the fire or the coal and the mixture has undergone combustion on the surface of the shale.

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* Quite recently there was a controversy in the *Coal Age* as to which stopping should be built and finished first. There should be no difficulty, after what has been described on pages 100, in deciding that the intake one should be built and finished first

Treatment of Cavities.

Sometimes a fire is found in a cavity in the goaf: this is due to the roof not settling, while a portion of the coal from the roof has broken down in fine slack condition and heated up. When such a cavity is opened the air moves in and out at regular intervals for a considerable time, a phenomenon which is termed "*breathing*." This is no doubt caused by a mixture of gas and air combusting on the hot material, but without flame; the mixture of hot gases resulting from the combustion occupy a greater volume than the unburnt mixture and some is forced out of the entrance. Then the gases cool and the steam condenses, with reduction of volume, so that more air is sucked in; this mixes with the gas and is burnt in the same way, and so the process goes on.

$$\begin{array}{ll} CH_4 + 2O_2 & = CO_2 + 2H_2O. \\ \underbrace{\text{2 vols.} + \text{4 vols.}}_{\text{6 vols.}} & \begin{array}{l}(\text{2 vols.} + \text{4 vols. steam}). \\ \left(\begin{array}{l}\text{Perhaps 8-10 vols. while hot, which become} \\ \quad\text{2 vols. on cooling and condensation of the} \\ \quad\text{steam.}\end{array}\right)\end{array}\end{array}$$

After a large gob-fire has been successfully dug out and removed to the pit top, the question arises as to what to do with the huge cavity, out of which perhaps a thousand tons or more of material have been taken. If it is gobbed up at once there is always the chance that the heating may recommence.

The author considers that the best way to treat such a hole is to leave it open for some weeks (keeping the roof well supported with brick walls), and then thoroughly to saturate the floor and sides, and later on the roof as well, with a strong solution of calcium chloride, applied with a garden syringe. After this it should be gobbed up with dirt and sand, each layer of this material being also wetted with the same solution as it is put in. Sometimes it is impossible to gob right up to the roof, but the process should be carried as far as possible, and when any reservoir has to be left it should be finally built off with bricks and mortar, after thoroughly syringing the roof with calcium chloride solution.

It cannot be too strongly emphasized that to leave a huge cavity in a gassy mine, where there may be a recurrence of fire, is a most dangerous procedure. Experiments have shown that some coals which have been once warmed and cooled are much more likely to heat up again than the original coals which have not experienced this treatment.

Self-extinction of Heatings.

It frequently happens that a heating does not develop into a gob-fire but gradually dies away of its own accord. In many instances the sweating stage has been detected and, after being kept under observation for some time, has disappeared without further result. Also the second stage, with its paraffin smell, has been noticed to continue for some time and then die away. Sometimes the first signs of a heating come, die away, recur, and finally develop to the gob-fire stage, but this is unusual.

Occasionally it has happened that on cutting through a goaf, when making a new road, the workers have come across charred wood and other unmistakable signs of a dead fire, although no fire had ever been observed in that locality. In such cases the fire has evidently been arrested by an increase in pressure from the overlying strata. This pressure acts in two ways; it tends to exclude air and, by improving contact, it causes heat to be conducted away more rapidly.

When the first signs of a heating are observed, it is the usual practice to diminish the ventilation and to push on as rapidly as possible with the adjacent working face, in the hope that the resulting pressure will come on to the heated spot and stamp out the fire, which it very frequently does.

In connection with the prevention of gob-fires by regulation of the ventilation, the reader is referred to page 112, dealing with the prevention of explosions by clearing the dangerous dust by reversal of the ventilating current. In pits subject to gob-fires, the reversal of the ventilation at week-ends, after stoppage of haulage on Saturday until a few hours before resumption of work on Sunday, would undoubtedly reduce the number of gob-fires very materially, especially that class which occurs in the goaf and which is apparently caused by a short circuiting of the air. There is little doubt that three-fourths of the fires of this class would never originate if this simple method was adopted.

Early Detection of Gob-fires.

Until recently the only method of detecting gob-fires in their early stage was to keep a sharp look-out for sweating in the roads, and for the evolution of gas which had the characteristic odours known to precede a gob-fire. However, as the result of a long series of laboratory experiments in 1911-1912, the author found that gob-fires could be detected, at a still earlier stage of their development, by *systematic gas analyses of the mine air*, and he was the first to put this method into practice.

The method has already been utilised for over six months in some mines and the results obtained show that it is possible to detect heatings when in a very early stage, and to locate them approximately. It is unfortunately not yet permissible to give any of the actual particulars of this work and details of the method employed, but no doubt the authorities who paid for its trial will in due course publish the results.

Testing stations for continuing this work have lately been established, and a well-known physiologist has been put in charge not only of the stations but also, indirectly, of the author's research. In view of this attempt to appropriate an idea and a line of work that were originated by the author, he takes this opportunity of claiming priority.

Use of Inert Gas.

One way of treating gob-fires with absolute safety is to feed the affected district immediately with air that contains a reduced percentage of oxygen. If the proportion of oxygen in the fresh air supplied is only 17 per cent., or a little less, the fire cannot make much headway and certainly cannot blaze up. Moreover the gas that is evolved cannot form an explosive mixture with such air, and thus the heated material can be dug out in perfect safety. To guard against too great a reduction of oxygen, one or two acetylene lamps must be employed to indicate the percentage, the remainder being, of course, electric lamps.

A still better plan is to have a constant supply of inert gas (prepared in the manner previously described in chapter X.) fed into the suspected wastes where heatings are most likely to occur, and so prevent any fires originating. The quantity of such gas required is comparatively small, being just sufficient to correct the changes in atmospheric pressure and to counteract any short-circuiting across the wastes.

As a rule, it is fairly well known in what districts the fires are likely to occur. Moreover, when first discovered they are usually very small, the amount of heated material probably being about as much as would go into a two-gallon bucket or so. But the exact position is unknown, and the fire rapidly spreads. Also the scourings, put in to find it, very often give it an easier supply of air and so, under present methods, it may be a big heating by the time the men get to it.

If a current of inert gas under pressure was led into the waste and all the openings were stopped up as thoroughly as possible, such a heating would be put out or prevented from spreading. The supply of inert gas need not be maintained for long, as it is only a matter of time (three or four weeks at most, in a normal case) when the pressure of the roof will act and put an end to all combustion, for the reasons previously mentioned.

After the first capital outlay the inert gas supply costs nothing except the expense of extending and repairing the pipe from time to time: such expense is trivial in comparison with the cost of the present system. Moreover, it would alleviate the anxiety and worry which these heatings cause and, still more important, it would bring absolute safety instead of diminished risk. For in spite of every care and precaution, the present system does occasionally fail and the trouble develops into a terrible disaster.

HYDRAULIC STOWAGE.

The only safe alternative to the use of inert gas for preventing these fires, is the system of *hydraulic stowage* or *mine filling*, as it is called in the United States, where the method was initiated (in the Pennsylvania anthracite fields). It has been used to a considerable extent in Germany, and is in use in France and Spain and in one mine in Great Britain.

The substance taken out of the coal-seam is replaced by material from above, consisting of sand, gravel, ground clinker or any other available material, cheap enough to be used and preferably non-combustible. This is washed down pipes about 7-inches in diameter and led to the wastes that require filling. The sand and other solid matter is deposited, while the water that drains away is pumped back and used over again. The pipes are made of mild steel with a cast-iron lining, and they appear to last fairly well except at the bends; these require renewal very frequently.

Under favourable conditions of dip and where suitable cheap material can be got without grinding, the cost does not exceed 6d. per ton on the total coal taken out, but where the conditions are not so favourable it may be as much as 2s. 6d. per ton.

The system was first introduced into Germany in 1903 at the Sulzbach and Altenwald Collieries, and it is now in use at eleven pits in that country.* The capital outlay was £700,000, the length of pipe being 42,000 yards. In 1910 the amount of coal extracted was 736,000 tons, and 577,900 cubic yards of material were "stowed."

The average cost was 2 marks per cubic metre of material stowed, or about 1·5 marks per ton of coal extracted, though at Lowensthal the cost was 2·5 marks per ton of coal.

Against the cost can be put the saving of coal pillars, as it is found that these can safely be removed from beneath railways and from under churches and other valuable buildings. It was for this reason, the saving in coal pillars and the prevention of damage by subsidence, that the system was originally adopted in America and in Germany. On working it, it was found that gob-fires never occurred in the wastes so treated.

Speaking generally, the system has led to economy in the cost of upkeep and to a decrease in the cost of timbering, but in pits where the strata is of a friable nature, as at Altenwald and Reden, the use of water has increased the cost of maintenance. It is claimed that the method has the following advantages:—

(1) Accidents from falls are less frequent.
(2) The output per worker is increased.
(3) Gob-fires are entirely prevented.
(4) Subsidence of the surface is rendered more gradual.
(5) Thick seams can be extracted at one working.

In a recent report of the U.S.A. Bureau of Mines (year ending June, 1912) it is stated that the coal wasted in the American mines amounts to 280 million tons per annum, and the Bureau is endeavouring to determine whether the adoption of hydraulic stowage would prevent this enormous loss.

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* Abstract *Colliery Guardian*, Nov. 1, 1912.

Similar waste occurs in this country; in the Barnsley Seam, for example, at least one-third of the coal is left in the waste. But it is doubtful if the method of hydraulic stowage could be got to work satisfactorily in England. In open competition a colliery would hesitate to increase its working costs by 1s. to 2s. per ton while its more fortunate rivals were free from this burden. Also, in some of the hotter mines (which are the only ones which have serious gob-fires) danger would be caused by the water inducing falls from the roof and sides. Moreover in such mines the air would get so moist that the health and working power of the men would be seriously affected. It is futile to replace one evil by another just as great or even greater.

REMOVAL OF ALL THE COAL WITHOUT HYDRAULIC STOWAGE.

It has been suggested from time to time that gob-fires would not occur if all the coal were taken out of the seam, for the fire could not exist in the absence of inflammable material.

In the mines where gob-fires occur, it is the custom to leave a large portion of the top coal (soft coal) and also some, if not all, of the bottom (soft) coal. Whether this coal could be taken out with safety, and whether by suitable treatment it could be made to pay for its extraction, are questions for mining engineers to decide.

There appears to be very little doubt at present, in the minds of the people directly concerned, that such a method is impracticable, that the extraction of the soft coal would not pay and that its removal would add to the risk of falls; but the method has yet to be tested. In one or two mines, where all the coal is removed, because the soft variety is quite saleable and because it can safely be extracted, gob-fires are unknown.

It is certainly easier, more economical and less dangerous to work, say, 5 feet to 6 feet 6 inches of good coal than to work 7 feet to 9 feet of coal, some of which is of inferior quality and difficult to market. But if the extra 2 feet to 2 feet 6 inches can be made to pay for the labour of extracting it, there is little doubt that it should be removed, provided, of course, that extra accidents can be prevented.

Up to the present the toll in human lives directly due to gob-fires has not been relatively great: extra danger from falls due to working the wider seam might easily cause a greater loss of life.

Conclusion.

In the absence of faults, gob-fires should be of rare occurrence. The shaft pillar fires, which have been amongst the worst in the Barnsley Seam, are not likely to occur in new mines, if the managers and mining engineers realise at the start the risk of fire in them and take effective steps, at the very beginning, to guard against it.

If a large number of fires occur in the goaf, in absence of faults, some defect in the method of working is clearly indicated. Either the ventilation is excessive or the method of making the packs (or the number or dimensions of these) does not suit the particular roof that is being treated. The risk of fires at big faults cannot be avoided by any present method of working. Such fires can only be prevented by hydraulic stowage or by the use of inert gas.

The question has recently been raised by influential people, who, however, know little of gob-fires, whether in a district where a gob-fire exists the men should be withdrawn and part of the mine shut down until the fire has been dug out or extinguished. The answer to this is that, if such a course were followed, the result would be an increased number of gob-fires. If the coal face is kept straight and steadily advancing, there should be very little risk of gob-fires in the absence of faults and strikes. If faults occur, the only remedies are inert gas or hydraulic stowage.

In the event of a general strike, it should be possible to arrange beforehand that pits liable to gob-fires, or the parts of such pits liable to fires, should be worked during the strike, the coal obtained to go into bond (as it were) under the joint control of the owners and the men's representatives. For the occurrence of gob-fires is as detrimental to the interests of the men as it is to that of the owners.

APPENDIX.

SOME NOTES ON FIREPROOFING TIMBER WITH SPECIAL REFERENCE TO THAT USED IN MINES.

Timber is a very combustible material; few people realise how highly combustible it is when it is quite dry, a condition which, however, can only be brought about by heating it to over 100° C. It has the property of retaining a large quantity of moisture at any ordinary temperature in perfectly dry air and even in a vacuum. Chorley and Ramsay found that, even after drying *in vacuo* for a month, oak still contained 13½ per cent. of hygroscopic moisture.

As soon as wood is deprived of its hygroscopic moisture in this way, it heats up spontaneously and becomes much hotter than the vessel in which it is heated, even when no air is present. It contains *endothermic* compounds which by their rearrangement and decomposition evolve much more heat than is liberated by the coals described on pages 94 and 132.

Most varieties of wood at a little above 100° C. give off gas, water vapour, etc., and then permanent gas at higher temperatures. Some woods such as deal give off inflammable gas at about 280° C. but the author has found that inflammable gas is evolved from spruce (which is often used for pit props) at about 200° C. and the gas given off will ignite with explosion when the tube at 300° C. is opened so as to admit air.

To make timber absolutely fire-proof is not a practicable proposition, but wood can be so treated as to render it flame-proof. When this has been done the action of intense heat is merely to char it, but not to set it on fire in such a way that it can *spread* the combustion, and for practical purposes this may be regarded as fire-proof timber.

It is over three hundred years since attempts were first made to fire-proof timber; many of these older methods took the form of applying paints made with mineral matter, such as silicates, for coating the surface of the wood. Most of such methods ended at the experimental stage, and even Sir Humphrey Davy and Faraday, who both spent considerable time on this subject, failed to solve the problem from a commercial or technical standpoint, although they succeeded in rendering small pieces of wood fire-proof in the laboratory.

To make wood fire-proof the timber must be thoroughly impregnated with the fireproofing material, and the method must be varied with different kinds of timber and even with the same kind if grown in different localities.

For commercial purposes the number of substances which can be used for fireproofing wood is limited by various factors. If the timber is to be used for decorative work there are practically only two materials that are thoroughly satisfactory, viz., ammonium phosphate and boracic acid. Wood properly treated with solutions of these materials gives timber which can be worked and used for the same purposes as ordinary untreated timber, with, of course, the additional advantage that it is fireproof and also proof against rot and vermin.

There are many cheaper materials which will fireproof timber satisfactorily, such as ammonium chloride, ammonium sulphate, calcium chloride, magnesium chloride, zinc chloride, zinc sulphate, stannous chloride and alum. Where the timber is not required for use in building or decorative work, common salt can also be used, but timber treated with this is hygroscopic and for most commercial purposes its use would not be permissible. Most of these fireproofing materials are very injurious to joiners' tools; the two singled out at the beginning of the list are, however, not destructive.

Ammonium phosphate and boracic acid are too expensive to be used for fireproofing pit props, and the most likely materials for these are calcium chloride and sodium chloride. If the props are cut to the required length before fireproofing, the material is not of much importance and at most would only cause a somewhat increased wear on the hand saws used in the pits.

In fireproofing the timber the wood is run on small trolleys into a large cylinder in which, by means of a vacuum pump, all air is extracted from the cells of the wood and the solution of the chemicals is then run in. The contents of the cylinder are then *placed under hydraulic pressure*, which must be carefully regulated, according to the character of the wood. Otherwise, if the pressure applied is too great, the cells of the wood will be destroyed and the strength of the timber impaired.

The completion of the impregnation process is indicated by the level on a gauge glass showing that the necessary quantity of liquid has been forced into the timber. This is then removed and dried at a temperature of about 80° F. Timber treated in this way is still combustible in a big flame but it will not spread combustion, and if impregnated with calcium chloride it would tend rather to retard than to help any spontaneous combustion in the goafs.

For superficially fire-proofing the surface of timber, so that it will not catch fire easily, one of the best materials known to the author is *glue*. Common bone glue (5 per cent. in hot water) is used and the timber is put into the hot solution for a few minutes; or, better still, a vacuum chamber is employed and the hot solution run on to the timber. Even painting the timber over with the hot glue solution is fairly effective, but with this method some kinds of glue are apt to crack off when dry.

The glue solution should have some antiseptic added to it before being applied to the timber. Carbolic acid or zinc sulphate acts quite well and the quantity used should be about 1 per cent. of the weight of the solid glue.

HYGROMETRICAL TABLE SHOWING RELATIVE HUMIDITY OF AIR AT DIFFERENT TEMPERATURES.

Difference between Wet and Dry Bulb Temperature. →	Dry Bulb Temperatures.	0°	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°	11°	12°	% Water by volume in Saturated Air.
% Saturation at	30 F	100	84	70	58	47	39	32	28	23	18	14	12	10	0·56
,,	40°	100	92	84	76	70	63	58	52	47	43	38	34	31	0·83
,,	56°	100	93	86	79	73	68	62	58	53	49	45	41	38	1·20
,,	60°	100	93	88	82	76	71	66	62	58	54	50	46	43	1·74
,,	70°	100	94	89	83	78	74	69	65	61	57	54	50	47	2·45
,,	75°	100	94	89	84	79	75	70	66	62	59	55	52	49	2·90
,,	80°	100	95	90	85	80	76	72	67	64	60	57	53	50	3·50
,,	85°	100	95	90	85	80	76	72	68	64	61	58	54	51	4·01
,,	90°	100	95	90	85	81	77	73	69	65	62	59	56	53	4·71
,,	95	100	95	90	85	81	77	73	69	66	63	60	57	54	5·50
,,	100	100	95	90	86	82	78	74	70	67	64	61	58	55	6·44

TABLE SHOWING DIFFERENCE IN COMPOSITION, ETC., OF DIFFERENT TYPES OF COAL.*

Class or Type of Coal	Composition.			Per cent Coke.	Nature and Appearance of Coke.	Calorific Power.	Industrial Calorific Power. lbs. Water heated from 0° C. and evaporated at 100° C. per lb. Coal.
	C.	H.	O.				
1. Dry coals with long flame	75-80	4·5 5·5	15·0-19·5	55 66	Powdery or slightly coked	8,000 8,500	6·7 7·5
2. Fat coals with long flame (gas coals)	80 85	5 0 5·8	10·0 14·2	60 68	Completely coked, but porous	8,500 8,800	7·6 8·3
3. Fat coals, properly so called	84 89	5·0 5·5	5·5 11·0	68 74	Coked, more or less puffy	8,800 9,300	8·4-9·2
4. Fat coals with short flame (coking coals)	89 91	4·5 5·5	5·5 6·5	74 82	Coked, compact	9,300 9,600	9·2-10·0
5. Lean coals or anthracite	90 93	4·0 4·5	3·0 5·5	82 90	Slightly coked, oftener powdery	9,200 9,500	9·0-9·5

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* "Carbonisation of Coal," Vivian B. Lewes, p. 44. (Table slightly modified.)

Table showing Candle-power of Various Types of Safety-lamps.*

Make.	Candle-power.
Cambrian (latest type)	0·4
Ackroyd and Best	0·4
Patterson	0·42
Wolf	0·80
Old type (Davy)	0·165

Table showing Total Coal Supply and Annual Production in European Countries.†

Country.	Production per Annum, in Tons.	Total Coal, in Millions of Tons.
Great Britain	236,130,000	140,000
Germany	119,350,000	150,000
France	34,780,000	17,000
Belgium	21,500,000	16,000
Russia	17,120,000	20,000

Table showing Number of Men killed each Year per 1,000 employed in Coal Mines of Various Countries.

Country.	Year.					
	1906.	1907.	1908.	1909.	1910.	1911.
United States	3·29	4·70	3·69	3·83	3·91	—
Great Britain	1·29	1·31	1·32	1·43	1·70	1·18
Austria	1·03	1·07	0·86	1·07	—	—
Prussia	1·97	2·40	2·71	2·04	1·98	—
France	‡7·17	1·10	0·95	1·17	—	—
Belgium	0·95	1·03	1·07	0·95	0·95	—

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* T. L. Llewellyn, *Trans. Inst. M. E.*, vol. xliv., part 1, p. 274.

† "Carbonisation of Coal," Vivian B. Lewes, p. 60.

‡ High figure caused by disaster at "Courrière"; the high figures in the United States are due chiefly to the abundance of gas and dust explosions (see p. 73).

TABLE SHOWING DEATH-RATE PER 1,000 PERSONS EMPLOYED AT COAL AND METALLIFEROUS MINES.

Year.	Underground Workers.					Surface Workers taken separately.
	Explosions of Fire-damp or Coal Dust.	Falls of Ground.	Shaft Accidents.	Miscellaneous.	All Causes Underground.	
1902 ...	0·092	0·686	0·154	0·438	1·370	0·687
1903 ...	0·020	0·832	0·102	0·396	1·351	0·895
1904 ...	0·031	0·753	0·126	0·438	1·348	0·831
1905 ...	0·251	0·758	0·106	0·404	1·519	0·720
1906 ...	0·076	0·773	0·104	0·472	1·424	0·767
1907 ...	0·057	0·755	0·133	0·511	1·455	0·761
1908 ...	0·157	0·741	0·111	0·458	1·467	0·740
1909 ...	0·272	0·736	0·108	0·505	1·621	0·670
1910 ...	0·579	0·760	0·111	0·467	1·917	0·748
1911 ...	0·041	0·721	0·124	0·422	1·308	0·725

INDEX.

PAGE
Abel, Sir F. 12, 63, 101, 121, 123
Accidents in mines 60
Acetylene 26, 128, 165
Air, composition of 36
Altitudes, effect of high ... 39
Altofts 68, 70, 79, 99, 101, 103, 110
  Experiments ... 80-84
  Explosion 77
Aluminium carbide 14
Aluminium dust 92
Alveolar pressure 37
Amberites 4, 15
America, explosions in 60
Ammonia 11
Ammonium sulphate 11
Analysis, air at face 44
  Blasting powder gas ... 96
  Coal dust 17
  Coal gases 17, 18
  Dried and heated coal ... 134
  Gas 55
  Mine atmosphere 164
Anderson 10
Animal blood 49
Anthracite ... 5, 66, 83, 88, 93, 108, 126, 138, 155
Apnoea 38
Appalachian coal 137
Argon 13
Arley seam 129
Atmosphere, mine 97, 100, 102, 104, 105, 127, 164
Atmospheric pressure 142, 145, 147
Austrian commission 18, 64, 110
Autoxidation ... 30, 132, 155, 156

Bacteria 7, 14, 15, 36, 51, 131, 132, 154, 156

PAGE
Barnsley seam ... 158, 168, 169
Barometer changes 145
Bedson, Prof. ... 9, 16, 18, 86, 95
Bergius, Dr. 4
Bert, P. 40
Berthelot (& Vieille) ... 56, 57
Bin experiment 148
Bird test 51
Bischoff 12
Bituminous coal 4, 5, 7, 93, 143, 144
Black damp ... 43, 50, 104, 115
Blackett, W. C. 79
Blasting powder, analysis of products 96
Blowers 13
Blown out shots ... 67, 69, 73, 95, 113, 116
Bog iron ore 33, 124
Bone, Prof. 33
Brancepeth 71, 95
British Association 127
Brown coal 3, 86, 93
Brucetown 84
Buddle, J. 61
Bunsen 55
Bureau of Mines, U.S.A. 9, 59, 137, 147, 151, 167
Burgess (& Wheeler) 121

Cadeby 74, 99, 127, 159
Cadman, Prof. 47, 105
Calcium carbonate 89
Calcium chloride 49, 163
Calorific intensity 24
Calorific power 8, 20, 23
Camerton 71
Campagnac 62
Camphausen 65, 110

PAGE
Candle flame, test 36
Cannel 4, 5, 7, 8, 93
Cannon, ignition by ... 62, 83
Caps, flame 144
Carbohydrates 7
Carbon bisulphide 21
Carbon dioxide 4, 7, 8, 12, 14, 20
  Absorption by coal 135
  Action in breathing 37, 38, 42
  Amount in air 42
  Cylinders 151
  Influence of increased 42, 126
  Influence on ignition 89, 106, 111
  Legal quantity 151
Carboniferous period 1, 6
Carbon monoxide 21, 22, 23, 26, 49
  In mine air ... 49, 143, 160
  Poisoning 49, 50, 51
  Removal of 125, 128
Carbon residuum 6, 7, 8
Carboxyhæmoglobin 49
Cargoes, coal 148, 150
Catalytic action 30, 33, 92, 123, 124, 130, 154, 156
Caustic soda 10, 49, 52
Cavities, treatment of 162
Cellulose 4, 6
Chambers, W. H. 74, 127, 159
Charcoal, mineral 3
  Wood 84, 87, 90
Chesterfield Institution 63
Clark, H. H. 59, 62
Classification of coal dusts ... 65
Club mosses 6
Coal, absorption of gas by 16, 30, 104, 115, 133, 134, 138, 140
  Analysis of ... 17, 134, 174
  Artificial production of . 4
  Caking of 8
  Catalytic action of 123, 154, 156
  Cementing material of ... 8
  Constituents of ... 5, 7, 8
  Distillation of 3, 6
  Durham 9, 10
  Face 66, 68, 69, 97, 103, 105, 120

PAGE
Coal (*continued*)—
  Friability of 91
  Gases in 12, 17, 18
  Influence on civilization ... 1
  Origin of 1, 2
  Oxidation of 5, 6, 30
  Scotch 10
  Smokeless 8
  Spontaneous ignition of ... 135
  Ultimate composition 5, 9, 10
Cochrane (& Morrison) 62
Coke 8, 11
Coke dust 87
Coked dust 80
Coking power ... 8, 9, 10, 11, 133
Colloid metals 32
Combustion 20
  Heat of 20
  Rapid 55
  Spontaneous 30, 131
  Surface or flameless ... 32
Commentry 81, 135
Commission, Austrian 18, 64, 110
  N.S.W. 146, 147, 148, 150
  Royal ... 66, 73, 101, 146
Committee on explosions ... 88
Composition of coal 5
Condensation 5, 15, 155
Constituents of coal ... 5, 6, 8
Copper 124
Courrières 50, 61
Creeps 15
Crevices, dust in 99, 119
Cyanogen 22

Dant 16, 17, 141
Davy 32, 55
Deaths in mines ... 60, 72, 175, 176
Decay of vegetation and wood 4, 7, 13, 14
Denaby 159
Detection of gob-fires 164
Detonating mixtures ... 22, 25, 54
Detonation 55, 56
Diffusion 143

PAGE
Digging out gob-fires 161
Dip of strata 15
Dissociation 25
Distillation of coal .. 3, 5, 6, 19
  Hypothesis 94
Dixon, Prof. 22, 58, 92
Draught, influence of 115
Drumpeller 71
Dryness of mines 67, 71, 73, 120
Dulong (& Thénard) 32
Dunstedt (& Buriz) 155
Durham coal ... 9, 10, 16, 17
Dust, absorption of gas by 16, 91, 94
  Age of 94
  Analysis of 81
  Artificial 110
  Classification of 65
  Degree of inflammability 65, 87, 88, 102
  Distribution in mines 67, 74, 83, 98, 99, 119
  Disturbance of 96
  Drying of 91
  Effect of excess 79
  Explosions 77, 102
  Fineness 66, 68, 76, 86, 102, 111, 130
  Gas in 95
  Ignition 105, 109
  Ignition temperatures 87, 88, 90, 92
  In suspension 68, 76, 98, 110, 111, 116, 130
  Inert 89
  Influence of quality... 86, 130
  Influence of quantity 85, 116, 130
  Method of testing 106
  Prevention of ... 74, 97
  Removal of ... 75, 76, 118
  Required for explosion ... 80
  Rôle in explosions 60
Dynamite 54, 65, 86

Edford colliery 67
Electric lamps 165

PAGE
Electric sparks 25
Electricity in mines 58, 59, 119, 127
Electrons 35, 58
Electrolytic gas 22, 25
Elemore 68, 70
Enclosed space, flames in ... 26
Endothermic substances 94, 132, 171
Energy, production of 1
Enzyme action 14, 31, 132, 154, 156
Equilibriator 124
Errors in theory of combustion 55
  Text book 55, 146
Eskmeals 81, 87
Essential oils 7
Ethane 18, 21, 22
Ethylene 23, 26, 121
Exhaled air 36, 44
Experimental explosions ... 80
Explosives 54, 65
  Wave 57, 58
Explosions, against current 78, 97, 99
  Experimental 80
  Influence of obstruction ... 84
  Mechanism of 54
  Prevention of ... 105, 118
  Stoppage of 68, 71, 78, 79, 84, 112, 129
  Theory of 66
  Violence of 71
Extinction of flames 26

Falls 129, 144, 168
Faraday 61
Faults 15, 141, 144, 159
Fayol, H. ... 133, 135, 145, 154
Ferment action 7, 14, 15, 132, 154, 156
Fernie mines 18
Ferric oxide 20
Firebrick 124
Fireclay 31, 33, 124
Fire-damp 12, 15
  In ignitions 62
  Influence on dust explosions 101
  Limits of ignitability ... 121

PAGE
Fish remains 4
Fixed carbon 5
Flameless combustion 32
Flames, movement of 29
Flashes 161
Flue gases 33
Fraser (and Hoffman) 9
Friability of coal 91
Fulminate 54, 57
Fungi 7
Furnace gases, use of ... 124, 128

Galle, E. 14
Galloway, W. ... 62, 66, 67, 129
Garforth, W. E. 78, 130
Garswood Hall 63, 121
Gas analysis 55
Gas engine exhaust 124
Gas in coal ... 12, 16, 17, 18
Gassy seams 158
Gerrard, J. 116
Glue refuse 132
Goaf 141, 144
Gob-fires 48, 50, **139**
  Age of 140
  Cost of 158
  Detection of 164
  Effect of strikes 169
  Favourable conditions ... 145
  Origin of 141, 154
  Phenomena 139
  Prevalence 158
  Spread of 156
  Timbers in 147
  Treatment 158
  Varieties of 141
Gob stink 141, 143, 161

Haemoglobin 40, 49, 50
Haldane ... 42, 43, 45, 53, 121, 128
Haldane and Meachem 152
Hall, Sir H. ... 62, 64, 68, 116
Hamstead 152
Haswell 61
Haulage-ways 67, 68, 74

PAGE
Health of miners 51, 60, 75, 104, 127, 128, 168
Heat of combustion 20
Heise (and Thiem) 58
Helium 12
Henderson 10
Hill, Dr. L. ... 40, 43, 46, 127
Hoffman (and Fraser) 9
Homologous series 21
Houghton 67
Hulton 129
Humic acid ... 7, 20, 30, 155
Humic coals 4
Humus bodies 6, 7, 8
Hydrocarbons 3, 6, 8, 11, 18, 31, 143, 144
Hydrogen ... 8, 11, 13, 21, 23, 26
Hydrogen peroxide 36
Hygrometers 47
Hygrometrical table 174

Ignition, origin of 67
  Source of 25, 26, **58**, 65, 86, 87, 95, 102, 121, 160
  Temperature 21, 22, 88, 90, 138, 144, 148
Incandescent lamps and filaments 58, 59
Inert gas 22, 24, 25, **123**
  Use of 165
  Cost of 166
Inorganic ferments 156
Intake haulage-ways 71, 77, 83, 98, 99, 103, 112
Intensity, calorific 24
Ionisation 58
Iowa mines 112
Iron, combustion of ... 20, 24

La Clarence 84, 130
Lancashire pits 69
Lead acetate solution 52
Le Chatelier (and Mallard) 22, 56, 63, 101
Lehmann 51, 58

PAGE
Lemaire 59
Lepape, M. (and Mouven) ... 12
Lewes, V. B. 10, 151
Liévin 81, 84, 87
Lignites 3, 5, 7, 138
Ligno-cellulose 6
Lignose 6
Limited supply of oxygen 27, 33, 39, 89, 104, 106, 109, 120, 126, 165
Limits of ignitability 25, 26, 105, 121, 144, 160
Llan colliery explosion 62
Lomax, J. 4
Longwall working 159
Lycopodium 6, 87, 88

Mahler 50
Mallard (& le Chatelier) 22, 56, 63, 101
Marcasite 150
Marreco, Prof. 62
Marsh gas 14, 16
Mechanical structure of coal ... 4, 5
Metals, catalysis by ... 33, 35
Methane, 4, 7, 12, 16, 18, 21, 23, 25, 27, 32
  Combustion limits 105, 121, 122
  Formation in coal 154
  Ignition temp. 90
  Occluded 84, 94
Micrococci 14
Microspores 4
Micro-study of coal 4, 6
Mineral charcoal 3
Mitscherlich 23
Moisture in air, ... 45, 75, 145
  Influence on combustion 145, 148
Moisture in mines ... 71, 75
Monongah 73, 86
Moore, Prof. B. 43, 128
Morrison (& Cochrane) 62
Mossfields 68
Mother of coal 3, 141
Moureu, M. (& Lepape) 12
Mouse test 51

PAGE
New South Wales commission 146, 147, 148, 150
Nitrogen, in coal 11, 12
  Ignition temp. 21
  Iodide 54
Nitrocellulose 52
Nitro-glycerine 52
Nitrous fumes 52, 53
Nitshill 66
Nystagmus 127, 128

Occlusion of gas 16, 18, 19, 30, 84, 94
  By dust 91, 94
  By coal 104, 115, 134, 138, 140
Olefiant gas 12
Optimum temperature ... 32, 132
Origin of coal 1, 2, 15
Oxidation products of coal ... 6
  Slow 20, 30
Oxy-coal-gas 24
Oxygen, administration of ... 50
  Combustion with 20
  Contents of coal ... 93, 138
  Effect of increased ... 90, 111
  Influence on dust ignition 103
  In respiration ...37, 38, 127
  Legal quantity 97
  Occlusion of 16, 20, 91, 104, 115, 134, 138, 140
  Reduction of 27, 33, 39, 89, 104, 106, 109, 120, 122, 126, 128, 165
Oxyhaemoglobin 37
Ozone 36

Packs 169
Palladium 31
  Chloride 51
Paraffin smell 137, 139, 140, 143, 163
Peat 4, 5, 7, 23
"Peat to anthracite" theory ... 2
Phenol 9
Phosphoretted hydrogen 21, 131
Phosphorus 131
Pillars 141

PAGE

Pioneering wave 79
Pittsburg 60, 85
Platinum 32, 88, 92
Playfair, Sir L. 12
Pockets... 13
Poisoning 50, 51
  Carbon monoxide ... 49, 51
  Nitrous fumes 53
  Sulphuretted hydrogen ... 52
Power, calorific 23
Pressure, influence on ignition temp. 23
  Of explosion 57, 58, 84
Prevention of explosions 105, 118
Props 83, 147
Propagation of combustion 26, 160
  Of flame 56, 57, 58
Pyridine 8, 9, 10, 11
  Extract 87
Pyrites, influence of 135, 136, 150, 155
Pyrophoric metal 21, 131

Radioactive changes ... 1
Radium 1
Reduction of oxygen 27, 33, 39, 89, 104, 106, 109, 120, 122, 126, 165
Removal of all the coal 168
Removal of dust 75, 76, 118
Renault 14
Reports on explosions ... 70, 73
Resinous bodies ... 4, 6, 7, 8, 11
Respiration 36, 45
  At high altitudes 39
  Effect of moisture on ... 46
Respirators 49, 52
Return wave 80
Return ways 67, 68, 98, 99, 103
Reversal of air current 76, 100, 118, 164
Rice, G. S. 60, 72, 85
Richters, Dr. 133
Risca 15
Risks of mining 60

PAGE

Roadways, extent of 98
  Fires in 120
Roberts ... ...
Roof, settling of 162, 163
Royal Commission 66, 73, 101, 146
Ryhope 95

Saarbrücken 64
Safety bill 97, 119
  Lamps 60
Sampling of mine air 100
Sand, use of 160
Schists 136
Scotch coal 10, 66
Scouring 159, 165
Screen dust .. 74, 97, 111
Seaham ... 63, 68, 69, 70, 101
Self-extinction of heatings ... 163
Shaft pillars 141
Shale dust 71, 89, 130
Short circuit of air 105, 139, 142
Shots, overcharged 77
Shot-firing, influence of 67, 71, 72, 95, 104, 113
Smokeless coals 8
Smoky chimneys 33
Sodium bicarbonate 89
Solvents, action on coal... ... 6, 9
Source of ignition 25, 26, 58, 65, 86, 87, 95, 102, 121
Sparks, ignition by 57, 58, 59, 95
Specific heat 24
Spontaneous combustion 30, 131
Sporangia 4
Spores 4, 6
Staffordshire mines 67, 68, 146, 158
Starch dust 87, 88
Steam coals 151
Stone dust 75, 78, 84, 102, 108, 118, 129, 160
Stoppings 99, 159, 161
Storage of coal 138, 147
Subsidence 167
Sugar dust 87, 88
Sulphides 51

PAGE
Sulphur 88, 151
Sulphur dioxide, removal of ... 37
Sulphuretted hydrogen 12, 21, 160
  Removal of 51
  Tests for 51, 52
Sunlight, influence of 54
Surface combustion ... 32, 33, 162
Surface, influence of 18, 21, 25, 32, 33, 34, 55, 92, 123, 162
"Sweating" 139, 143

Taffanel, M. 79, 85, 87
Taffanel barriers 84, 85, 130
Tamping 65, 113
Tar 11
Temperature of ignition 21, 22, 88, 90, 138, 144, 148
  Of combustion 23
  Of mines 153
  Optimum 32, 132
  Wet bulb 45
Testing stations 164
Texture of coal 65
Thiem (and Heise) 58
Thompson, Sir J. J. 35
Thornton, Prof. 26, 59
Timber, ignition of 147
  Fireproofing ... 171, 172, 173
  Influence on gob-fires 147, 163
Timbers 80
Towers respirator 52
Trigger actions 54
Trimdon Grange 68, 70
Troubridge 16
Tubs 74, 75, 86
Tudhoe 68, 70
Tylorstown 71

Udston 68, 70
Ulmic acid 7
Unit of heat 23
United States, accidents in 72, 73, 112
  Experiments in 84
  Hydraulic stowage in ... 166

PAGE
U.S.A. Bureau of Mines 9, 59, 137, 147, 151, 167

Valenzuela, M. 40
Vegetation, decay of 4, 7, 13, 14
Velocity of combustion 56, 57, 58
  Of explosive wave 78
Ventilating current, effect of ... 97
Ventilation, degree of 104
  Increase of 60, 68, 69, 71, 78, 97
  Influence of 97, 103, 112, 114
  Reduction of ... 159, 163
  Reversal of 76, 100, 118, 164
Verner 112, 114, 115
Verpilleaux, M. 62
Violence of explosives ... 71, 77
Vital, M. 62
Volatile matter and] inflammability 92, 93
  In coal 5, 10, 11, 19, 87, 92
  Needless for explosion 87, 90, 93

Waggons 71
Wallsend 2
Waste 139, 147, 168
Water vapour, influence of 45, 47
Watering 47, 129
Wave of compression 79
  Of explosion 57, 58, 77
Weather, influence on gob-fires 145
West Stanley 68, 70
Wet bulb temperature 45, 47, 75
Wet and dry bulb thermometers 47
Whalley, Dr. 43, 104
Wheeler, Dr. 12, 121
White damp 160
Witnesses, evidence of 66
Woody fibre 3, 5, 6
Wullner (& Lehmann) 58

Yorkshire (S) mines 129, 145, 158

Zinc ethyl 21, 131
  Methyl 14
Zones, limiting 117
  Of combustion 137

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